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Contribution No. 379

Reprinted from
PHOTOGRAMMETRIC ENGINEERING
March
1949

OCEANOGRAPHIC FACTORS IN UNDERWATER DEPTH DETERMINATION BY AERIAL PHOTOGRAPHY[1]

H. R. Seiwell, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

THE wartime development of aerial photographic methods for determining depths of shallow coastal waters has opened up new practical and theoretical problems of ocean research. Based on the oceanographic requirements and techniques, aerial photo methods fall into two general groups. One group is concerned with evaluations of water depths from measurements of horizontal parallax of surface and bottom images on stereo photos, or from measurements of emulsion densities on photographs obtained from various filter combinations. The second group of methods is concerned with evaluations of depths and bottom gradients from characteristics of the photographed sea surface wave patterns.

2. It is the opinion of this writer that the second group shows greater promise of practical development. This is because of the ease and flexibility of practical operation combined with greater versatility, and because several independent checks of depth computations may be had from a single photograph. The wave pattern methods are applicable to any part of the world's coastal areas requiring only that it be possible to evaluate characteristics of surface wave patterns from aerial photographs. Uncertainty in their use lies in the fact that computations are based on somewhat uncertain theoretical interrelationships of wave properties, such as height, period, length, steepness and refraction as the surface waves advance from deep water over shallow sloping bottoms. Thus the oceanographic requirements of aerial photography tie in with the general problem of sea surface wave investigations. Like many problems of this category, the investigation ultimately reduces to one of controlled experiments and controlled observational programs.

3. The theoretical considerations forming the background of computation are drawn from classical hydrodynamics. Specifically they apply to surface waves of low steepness, that is waves whose height is less than one half per cent of the length. Thus wave velocity (C), wave length (λ) and depth (d) are related by:

$$C^2 = \frac{g\lambda}{2\pi} \tan \mathrm{h} \frac{2\pi d}{\lambda} \cdot \tag{1}$$

This relationship is graphed in Figure 1.

Substituting the fundamental deep water relationship of wave velocity, wave length and wave period

$$C = \frac{\lambda}{T} \tag{2}$$

in (1) we obtain

$$T^2 = \frac{2\pi\lambda}{g} \cot \mathrm{h} \frac{2\pi d}{\lambda} \cdot \tag{3}$$

[1] Contribution No. 379 from the Woods Hole Oceanographic Institution.

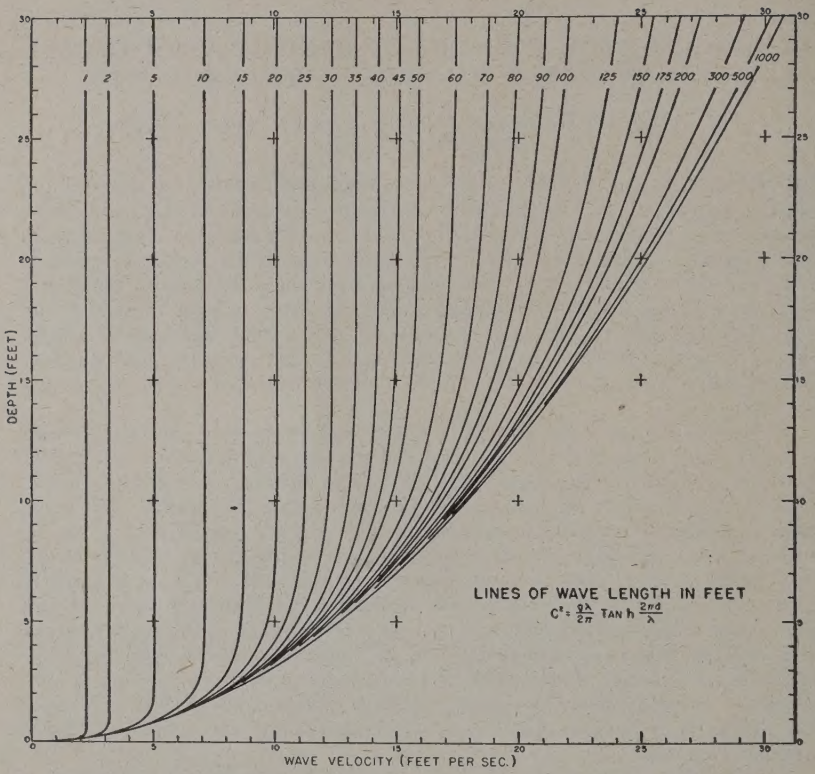
1 2 5 10 15 20 25 30 35 40 45 50 60 70 80 90 100 125 150 175 200 300 500 1000
LINES OF WAVE LENGTH IN FEET
$C^2 = \frac{g\lambda}{2\pi} \tan h \frac{2\pi d}{\lambda}$
DEPTH (FEET)
WAVE VELOCITY (FEET PER SEC.)

FIG. 1

This relationship is graphed in Figure 2.

4. Practical field experience has brought out that the method of equation 1 gives the most satisfactory results. Wave velocities are computed from the distances that identified wave crests move, as shown by successive timed photographs. Due to waves steepening as they advance into shallow water, wave velocities are somewhat higher than accountable by theory (Equation 1). To correct for this discrepancy, empirical factors are frequently computed from observations.

5. The analyses of differences between depths computed by the wave velocity method and by direct soundings from surface craft, show that occasionally the above theoretical relationship fails and large errors may result. Since it is these occasional large errors which in practice may be disastrous, a thorough investigation of shallow water wave properties in relation to sea surface roughness and sea bottom gradients is essential to placing the method on a practical working basis.

6. As an example of discrepancies between depths observed and depths computed by the wave velocity method, results of a series of experiments from Oahu are briefly considered. In these experiments, surface craft sounding profiles were made at right angles to the beach and were marked so as to be identified on

aerial photographs. Depth computations by the wave velocity method were made to coincide with the sounding profiles. The results of six such experiments are illustrated by Figure 3.

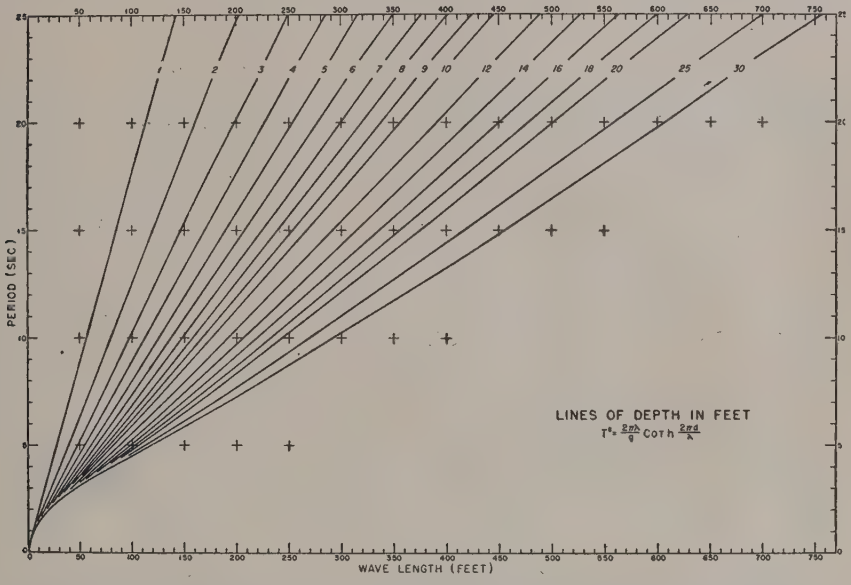

FIG. 2. Results from an experimental program investigating aerial photographic methods of underwater depth determination, undertaken by 6211 Beach Intelligence Unit, Pacific Ocean Areas, 1945.

7. Comparison of computed and observed values of Figure 3 shows that computed depths were usually greater. The discrepancy, however, is not as great as expected from first observation, due to the aerial sounded gradients being drawn from point to point determination; and the few large discrepancies are not the usual rule. However, it is these occasional large departures which greatly decrease the reliability of the method. They are not completely a result of erroneous photo interpretation, and photo measurements were checked after the first drawing of the profiles. They arise from a number of causes, and the possibility must not be excluded that reflections may play a significant role. The point is that they are not accountable by present theory. In the example, the most usually occurring depth discrepancy is of the order of two to three feet, excluding the occasional large departures, of profiles A and B in Figure 3.

8. A second method of aerial photo depth computation involves the period-wave length relation of equation 3. It has the advantage of requiring but a single aerial photograph and thus eliminates errors induced by the intervalometer. On the other hand, to apply the method, it is required that the aerial photograph cover offshore waters to a depth exceeding one half the length of the existing surface waves. It also involves the assumption that wave period remains constant as wave lengths and wave velocities diminish with their inshore progression.

9. Experiences during the recent war indicated that application of the

period-wave length relationship was less satisfactory than that relating wave velocity and length. In general, it was used only when intervalometer equipment for obtaining timed photographs was not available. The method appears to offer good possibilities which have as yet not been investigated.

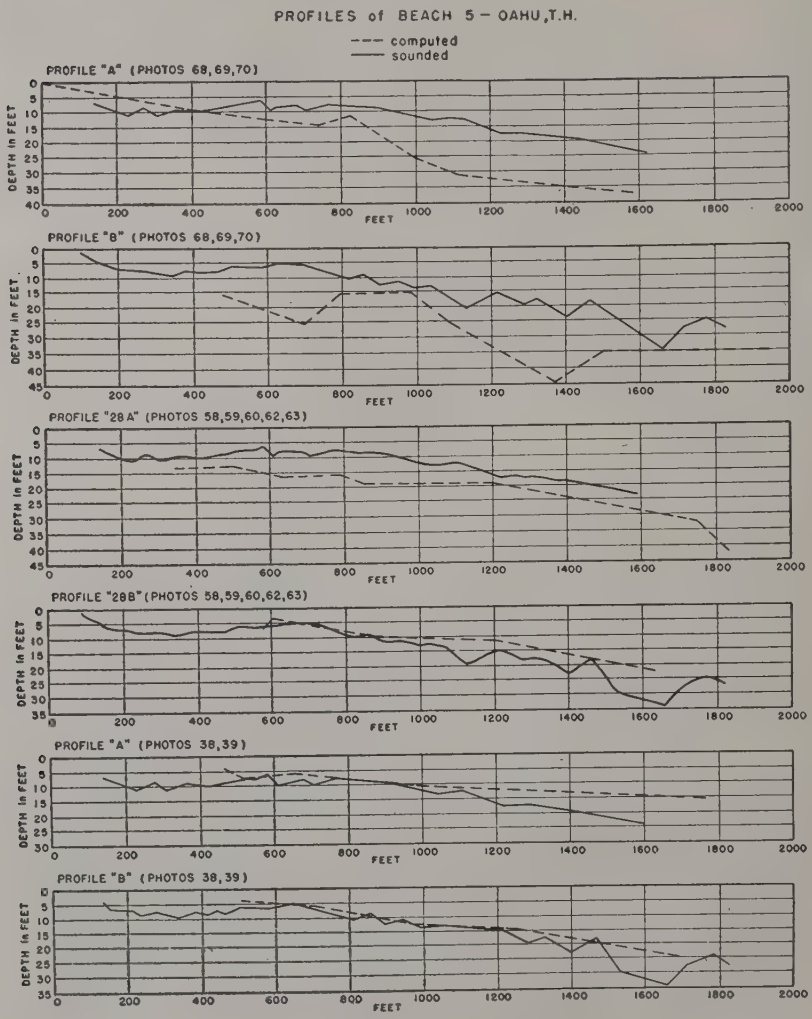

FIG. 3

10. The third application of shallow wave theory to depth computations from aerial photographs makes use of the refraction patterns of surface waves as they move from deep to shallow water. This occurs when deep water wave fronts make an appreciable angle of incidence with the shore line. As waves ad-

vance inshore, bending occurs as the crest velocity diminishes according to the ratio of water depth to wave length. Thus, in the case of a straight shore line, with offshore parallel bottom contours, the angle the deep water wave crests makes with the shore line (α_0) is related to the angle at depth, d, (α) by

$$\sin \alpha = \sin \alpha_0 \frac{C}{C_0} \tag{4}$$

where C_0 is the deep water wave velocity, and C the velocity, where d is less than one half the wave length. For this relationship, it is assumed that velocities of the wave crests depend only upon the water depth under the crest; that the wave crests advance perpendicular, and that energy does not flow laterally along the crest.

11. On the basis of a constant wave period we have from 4:

$$\sin \alpha = \sin \alpha_0 \frac{C}{C_0} = \sin \alpha_0 \frac{\lambda}{\lambda_0} = \sin \alpha_0 \tan \mathrm{h} \frac{2\pi d}{\lambda}. \tag{5}$$

For convenience we use

$$\frac{C}{C_0} = f\left(\frac{d}{\lambda_0}\right) \tag{6}$$

where the velocity ratio is related to the ratio of depth to deep water length, obtained as a numerical solution of the above. Hence, for practical use

$$\sin \alpha = \sin \alpha_0 f\left(\frac{d}{\lambda_0}\right) \tag{7}$$

α, α_0, λ_0 are read directly from the photographs. This method appears to be the least accurate of the three, although its possibilities have not been developed.

12. The adaption of geophysical field methods to the air needs no elaboration. In the case of Oceanography, air borne methods offer unlimited possibilities for obtaining critical data not heretofore possible except by tedious and expensive field programs. The problem now is to systematically investigate and record interrelationships of relevant oceanographic situations with the object of ultimately analyzing bathymetric situations of coastal areas from a minimum number of aerial photos. In this manner we reduce expensive and painstaking field programs to the more economical laboratory procedures. This is in addition to their military use during the next emergency. Thus the development of aerial photographic methods for determining underwater depths of coastal waters is one of the outstanding practical applications of oceanography. Future progress will require coordination of effort between the research oceanographer, the aerial photographic technician and the reconnaissance pilot, and in this manner research plans will be formulated along lines most suitable to produce useful results.

13. The application of physical oceanographic research to the aerial photo depth determination will now follow the same pattern as that for other oceanographic applications. Knowledge of the state of the sea surface, obtained from great masses of random observations have revealed that the general pattern conforms to the broad theoretical considerations of classical hydrodynamics. Nothing further is to be gained from analyses of the random and not too precise observations of the sea surface. Further progress in this direction, as in other applications of physical oceanography, depends on formulating and undertaking

systematic programs of controlled experiment or controlled observation. That is, field experiments and observations, aimed at the solution of specific problems and for which the analytical methods of reduction have been decided previous to their initiation.

14. In our specific case, we wish to obtain systematic experimental and observational data of highest possible accuracy and in such a fashion that the data lend themselves to the extraction of characterizing parameters. These parameters, representing the dynamic situations, permit numerical interrelationships to be established between the characteristics of deep water surface waves as they move in over sloping beaches. In this manner we do not exclude the possibility that the present observed discrepancies may be accountable by development of additional theory. We have reached the stage where this is now possible. Adequate instrumentation is available and the statistical procedures for reduction are known. It remains now to formulate the problems in exact terms and to undertake the specific experimental and observational programs.

Contribution No. 422

RADIOLOGICAL AND SALINITY RELATIONSHIPS IN THE WATER AT BIKINI ATOLL

William L. Ford

(Contribution No. 422, Woods Hole Oceanographic Institution)

Abstract--The circulation in Bikini Lagoon during the post-Baker Day period is deduced from the distribution of salinity and radioactivity. The use of the distribution of radioactivity as a method of determining the circulation is compared with other methods. The presence of radioactivity in the waters of the Lagoon as a result of the explosion presented a unique opportunity to obtain a partial evaluation of the radioactive tracer technique in problems of hydrography.

Figures showing a circulation scheme and the distribution of salinity and radioactivity are presented for the third, fourth, and fifth day after the underwater explosion. The circulation at this time was found to be abnormal due mainly to the unusual weather conditions. It has therefore been discussed with particular reference to the areas of concentration of the radioactive material in view of the possible bearing on studies of the effect of radiological contamination on marine flora and fauna at Bikini.

The use of radioactivity in tracing water motions at Bikini gave results which were in general agreement with those obtained by other methods.

Introduction--In this paper, the circulation of the waters of Bikini Lagoon in the period following the underwater explosion of the atom bomb is deduced from the distribution patterns of salinity and radioactivity, and the use of the distribution of radioactivity as a method of determining the circulation is compared with other methods. The presence of radioactivity in the waters of the Lagoon as a result of the explosion presented a unique opportunity to obtain a partial evaluation of the radioactive tracer technique in problems of hydrography.

The water samples upon which the radiological data are based were taken at the same time as the salinity samples, thus providing two independent but simultaneous methods for the study of the circulation system.

During the several months of field research at Bikini, considerable salinity data from both the Lagoon and surrounding ocean waters were obtained which showed that substantial salinity variations occurred within short periods of time, not only in the neighboring ocean surface waters, but also within the waters of the Lagoon. These variations throw light upon the exchange of water between the Ocean and the Lagoon and upon the circulation of the Lagoon itself. In this paper, consideration of these effects is largely confined to the post-Baker Day period; that is, to the period following the underwater atom bomb blast when they were of particular interest in connection with the dissipation of radioactive material. Baker Day was July 25, 1946, Bikini time.

Data--Water samples for both salinity and radiological analyses were obtained with the conventional Nansen bottle, and where both types of analysis were required they were taken from the same bottle, thus assuring an identical source. Surface samples were normally taken by bucket. Depths of sampling were determined by a metering wheel.

The salinity samples were analyzed within a few days of collection, and the radiological samples usually within 24 hr. Salinity was determined by the KNUDSEN [1946] method with an error not exceeding $\pm$ 0.03 $^{o}/_{oo}$. Radiological analyses were performed aboard the USS Haven under the supervision of K. G. Scott and G. C. Ewing. The units of activity are only relative; the actual units were not provided with these data for reasons of security. All measured activities have been calculated back to a standard time after the explosion in order to eliminate the complication of the radioactive decay rate. Although counts of less than 0.01 units of activity were recorded, values of less than 0.1 are in general treated as zero in this paper.

Discussion and results

Lagoon salinity changes and circulation--The normal circulation within the Lagoon and the rate of exchange with the ocean have been described by VON ARX [1948]. The observations were made under typical spring conditions and they show, among other things, that Enyu Channel, despite its size, was a relatively unimportant passage for exchange between ocean and lagoon waters. With the advance of summer, evidence accumulated that the influx of ocean water through Enyu Channel became a dominating feature. A review of salinity data now available indicates that the influx was not a simple flow subject to tidal variations, but from time to time became a substantial intrusion over and above normal flow. At least three such intrusions appeared to have occured during May, June, and July; in this paper only the intrusions which were in evidence to a marked and well-defined degree in the week including Baker Day are discussed.

Surface samples from representative points in the Lagoon were taken between 15 and 21 July (see Fig. 1). The average salinity was found to be 34.59o/oo and the surface was practically

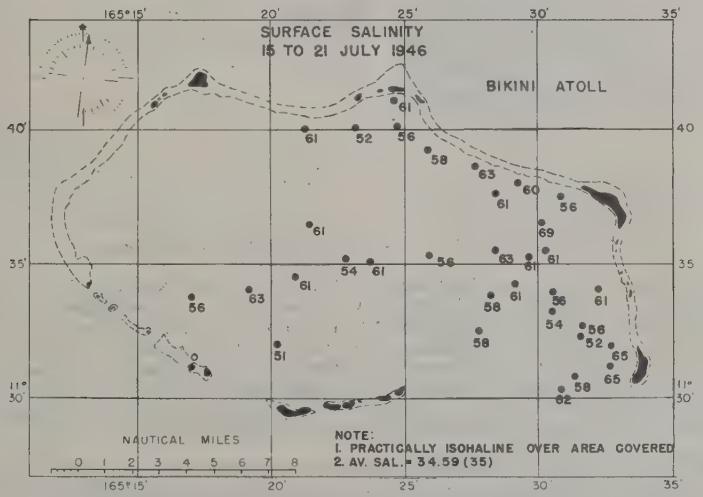

Fig. 1--Surface salinity in Bikini Lagoon for week ending July 21, 1946; average salinity, 34.59 °/oo for 35 observations, with little variation from the mean; the numbers alongside the dots are (observed salinity, 34.00 °/oo) × 100

isohaline from end to end. This being so, and since the average wind velocity was 12 knots, it was probable, on the basis of previous experience, that the water was also isohaline vertically. Outside surveys made at the same time (see Fig. 2) revealed the presence of water with salinity less than 34.30 °/oo just a few miles to the south of the Atoll and water of greater than 34.60 °/oo along the northern edge of the Lagoon. Earlier outside hydrographic cruises had also revealed the recurring presence of tongues or eddies in the upper 150 ft of the neighboring ocean waters whose salinity differed significantly from that in the Lagoon.

Following Baker Day, on July 28, 29, and 30, water samples were taken at depths of 0, 10, 75, and 150 ft at many points in the Lagoon. The results are plotted to show surface and vertical distribution in Figures 3 to 12. These surveys revealed that a marked change in the salinity distribution had occurred since the survey of the week preceding, and that the vertical structure was characterized by a thin surface layer of high salinity water in the central area, a layer of lower salinity varying in thickness from 50 to 150 ft underlying the surface and extending almost throughout the Lagoon, and finally by higher salinity in the deeper water.

This situation implies that the circulation system of the Lagoon differed in important aspects from the normal circulation that exists in the spring, since in none of the previous salinity surveys extending back four months had any such vertical structure been found. Influx of water over the eastern and northern reefs was reduced to a small fraction of the flow characteristic of spring.

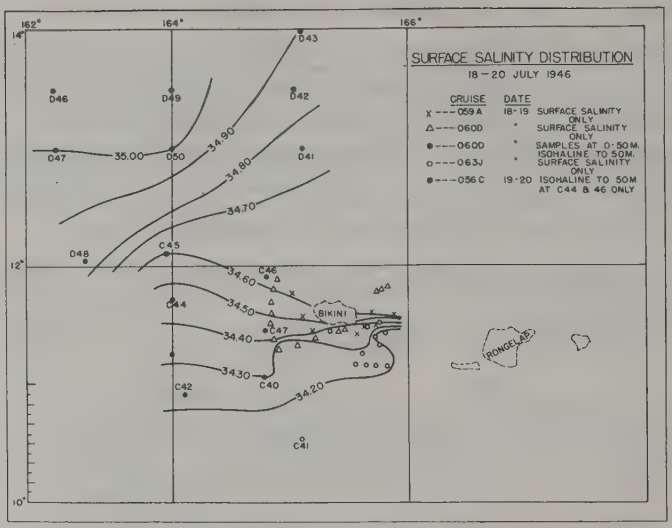

Fig. 2--Surface salinity distribution outside Bikini Lagoon

The driving force of this flow was the combined effect of the North Pacific swells and the strong northeast trades. In the latter half of July the swells had practically disappeared, and the wind was frequently from south of east and of low velocity. Thus an important source of new water for the Lagoon was no longer effective, and the major part of any exchange must take place through Enyu Channel and the southwestern passes. The salinity distribution, both inside and out, indicates that lower salinity water approached Enyu Channel from the southeast, entered the Lagoon, took an intermediate position between the surface and the bottom, and displaced lagoon water through the southwestern passes and over the submerged western reefs.

The wind of July 22 to 27 averaged six knots, blowing for two consecutive days from south-southeast, and the remainder of the time from east. The south-southeast wind, though very light (five knots), undoubtedly aided the inward flow across Enyu Channel.

Enyu Channel is of such size that an average inward flow of 0.5 knots would renew about one-half of the lagoon water in four days. It is estimated that during the seven days preceding July 28, 40 per cent of the lagoon water was displaced by lower salinity ocean water. This figure is based on an initial average salinity of 34.59 °/oo, a final average of 34.50 °/oo, and a salinity of 34.35 °/oo for the source water outside. If all of this water had entered through Enyu Channel, a net inward current of only 0.25 knots would be required.

A complex but interesting situation existed in the central part of the Lagoon in the post-Baker Day period which throws additional light on inward flow through Enyu Channel. The surface distribution of salinity, as given in Figures 3, 4, and 5, shows the development of a low salinity trough on July 29 extending from Enyu Channel to the center of the Lagoon. Only the remnants of a trough are visible on July 30. North-south sectional views through the central area (see Fig. 6, 7, and 8) show the nature of the situation perhaps a little more clearly. (The positions of the sections are shown in Fig. 3, 4, and 5). Section A for July 28 (see Fig. 6), shows a surface layer with a salinity greater than 34.50 °/oo extending at least two-thirds of the distance across the Lagoon from the north. By July 29, this surface layer had disappeared except for a patch adjacent to the southern islands. On July 30 (see Fig. 8), the 34.50 °/oo surface layer had reappeared in a form similar to that of July 28, but thinner. Section C for July 30 (west-east axis of the Lagoon: see Fig. 9) shows a low salinity pocket (less than 34.40 °/oo) located some three miles west of its apparent position the day before. To complete the picture, profiles, which run parallel to and one mile inside of Enyu Channel, are presented for July 29 and 30 (see Fig. 10 and 11). On July 29, a well-defined low salinity pocket was located in the middle of the Channel. Twenty-four hours later, it had largely degenerated. To sum up, it would appear that in the space of less than 48 hr

a mass of water of salinity less than 34.40 °/oo entered at about the middle of Enyu Channel and traveled approximately nine miles into the west-central part of the lagoon. The pocket extended down from the surface roughly 75 ft and was perhaps two miles wide. The average velocity of the pocket, 0.5 knots, in terms of spring conditions, would not be surprising, but is remarkable at this time in view of the sluggishness of the circulation elsewhere. The phenomenon indicates again that the Lagoon was subject to intrusion of ocean water across Enyu Channel and illustrates the extraordinary nature of the circulation pattern during the latter part of July.

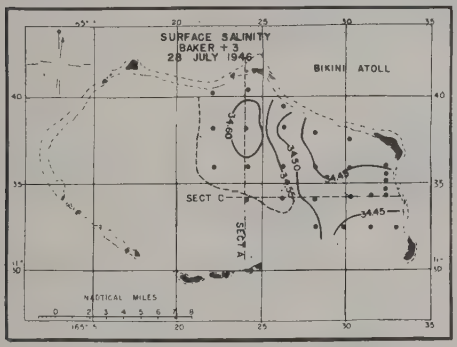

Fig. 3--Surface salinity in Bikini Lagoon, July 28, 1946

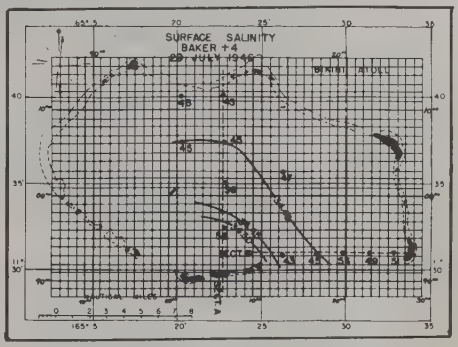

Fig. 4--Surface salinity in Bikini Lagoon, July 29, 1946; the grid, used for locating positions within the Lagoon, is also shown

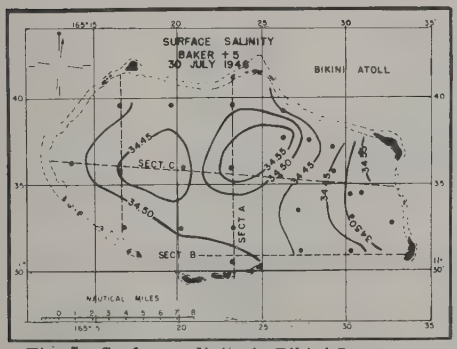

Fig. 5--Surface salinity in Bikini Lagoon, July 30, 1946

A further insight into the circulation of the Lagoon at this time is given by other changes that occurred between July 28 and 30 in the distribution of salinity. The very light winds and intrusion of ocean water of lower salinity that characterized the Baker-Day period must have led to a great reduction in the normal overturning, wind-driven circulation. The return of the easterly winds at velocities above ten knots on and after July 28 tended to re-establish the normal current system. A comparison of Figures 3 and 5 shows that the water in the lee of Bikini which had a low surface salinity moved westward, with the development of a current along the northeast reef and a broad band of higher salinity water along the eastern reef. This water originated in the return bottom current which upwelled in the eastern end of the lagoon. The development of this upwelling zone is illustrated by comparing the sharp upward swing of the isohalines near the east reef on July 30 (see Fig. 9) with those on July 28 (see Fig. 12). If the edge of the upwelling zone is defined as the position of upsweep of the isohalines, this would place the edge about 4000 yd from the midpoint of the east reef. This agrees closely with the estimate derived from the distribution of radioactivity.

Radioactivity as a tracer for the circulation of lagoon water--The lagoon circulation may also be deduced from the distribution of radioactivity, and the results compared with those based on direct current measurements, model studies, and salinity distribution. The activity data has been plotted in terms of iso-activity contours at three levels, surface to ten ft, 75 ft, and 150 ft, for July 28, 29, and 30 (see Fig. 13 to 21). A consideration of these contours which follows reveals that not only do the radiological data give a picture of the circulation of the Lagoon which is in general agreement with that deduced by other methods, but they give more detailed information than did the salinity observations. This may be largely attributed to the fact that the activity was moving from a source of high concentration to areas of low concentration, while, on the other hand, salinity differences at Bikini were very small, often being only two or three times the experimental error.

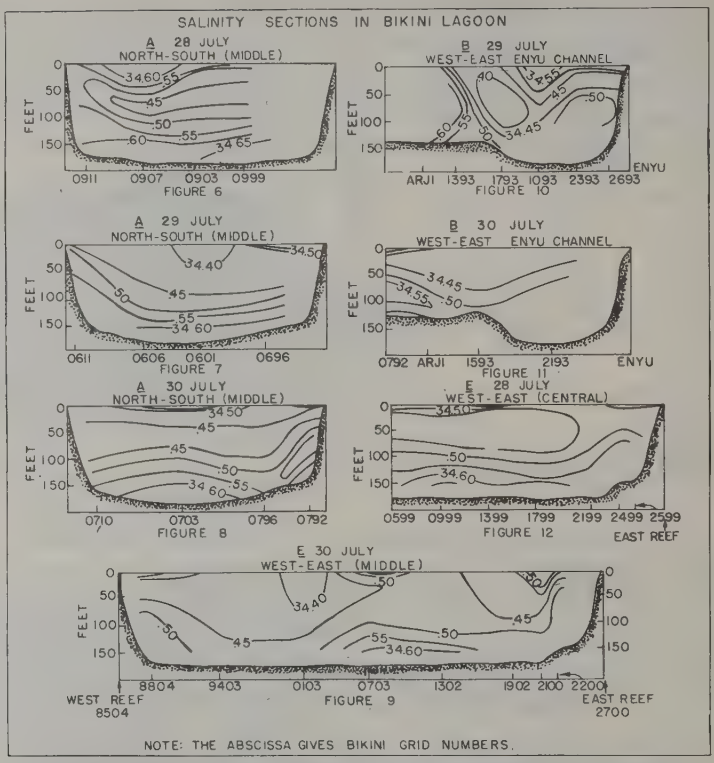

Fig. 6-12--Salinity sections in Bikini Lagoon; the abscissa gives Bikini grid numbers, the positions of which are shown in Figure 4

The changes in the activity distributions from July 29 to 30 show that the upper layer (down to at least 75 ft) of the lagoon water in the northwest was moving westward at about 0.15 knots (compare Fig. 16 to 21). In the central part, the surface iso-activity lines had moved farther west than those at 75 ft, indicating thereby that the 75-ft level in this area was in the transition zone between the surface and bottom currents, and that the surface layer became thinner toward the eastern end of the lagoon. The deep water is shown to have been moving in a generally eastward direction as a return current, since no appreciable activity was found at 150 ft except in the region of upwelling along the eastern reef and in an isolated patch extending south from Amen Island. The region of upwelling is quite well defined by the fact that the positions of the iso-activity contours at 75 ft correspond closely with those of the 150-ft level (see Fig. 20 and 21). Evidence of the sinking that would be expected in the western end of the Lagoon is shown by the significant amount of activity found from surface to bottom in that area (see Fig. 19, 20, and 21), while somewhat farther east the activity near the bottom was zero. These aspects of the circulation pattern as of July 30 are in general agreement with the basic lagoon circulation described by Von Arx, and are summarized in a current diagram (see Fig. 22). However, there are marked deviations which will now be examined.

The upper 75 ft (at least) of the lagoon water was divided into two systems during the period under consideration (July 28 to 30) by a rather narrow dividing zone running northwest from Enyu Island (see Fig. 19). The northern system contained the activity, the remaining area being virtually uncontaminated. There was no movement of the activity across this zone of demarcation except in the western half of the lagoon, despite the prevailing easterly wind. Two

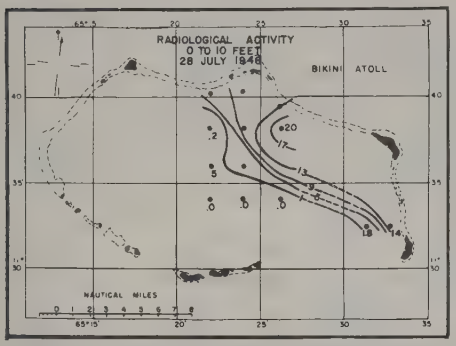

Fig. 13--Radiological activity in Bikini Lagoon, 0 to 10 ft, July 28, 1946

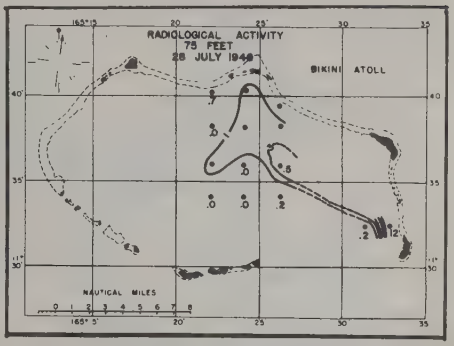

Fig. 14--Radiological activity in Bikini Lagoon, 75 ft, July 28, 1946

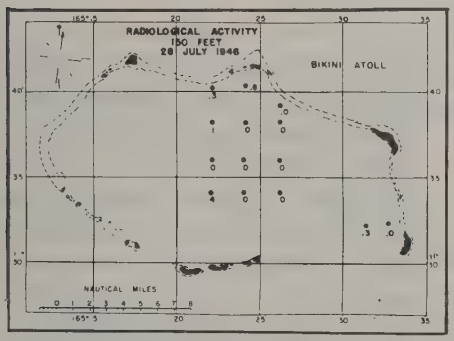

Fig. 15--Radiological activity in Bikini Lagoon, 150 ft, July 28, 1946

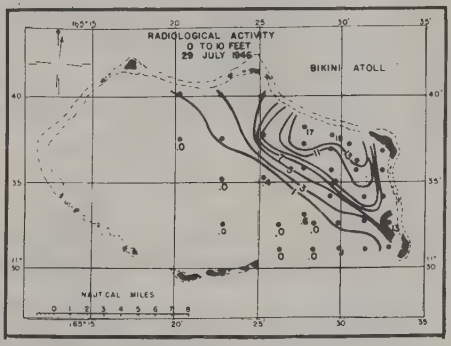

Fig. 16--Radiological activity in Bikini Lagoon, 0 to 10 ft, July 29, 1946

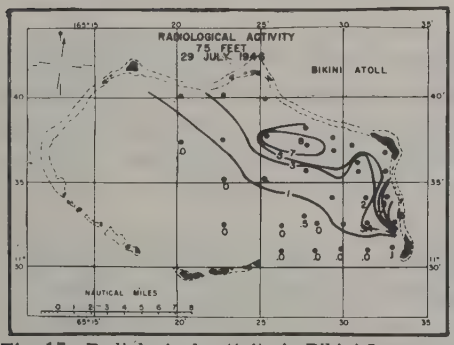

Fig. 17--Radiological activity in Bikini Lagoon, 75 ft, July 29, 1946

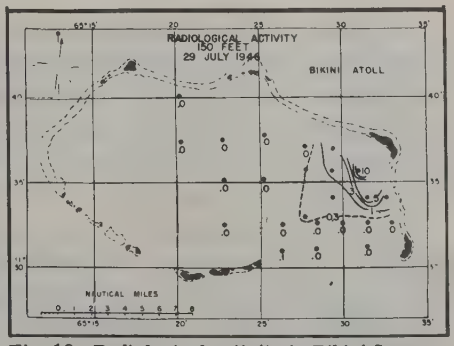

Fig. 18--Radiological activity in Bikini Lagoon, 150 ft, July 29, 1946

complementary factors would appear to explain this phenomenon: First, the intrusion of ocean water through Enyu Channel which was indicated to have occurred by an analysis of the salinity distribution; second, the low values of the surface diffusion rates which would be expected to exist in a narrow band along the zone of demarcation. (Diffusion rates are discussed by VON ARX [1948]). The division of the Lagoon into two distinct systems was shown to occur in model experiments [VON ARX, 1948] in which an Enyu Current was created by a southeast wind.

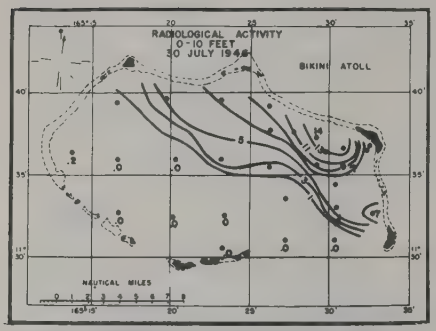

Fig. 19--Radiological activity in Bikini Lagoon, 0 to 10 ft, July 30, 1946

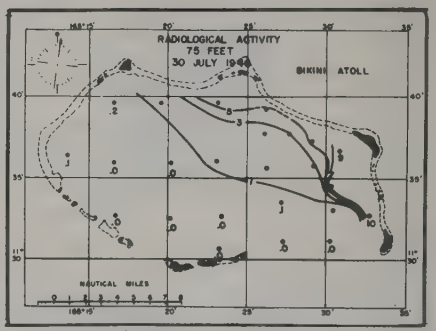

Fig. 20--Radiological activity in Bikini Lagoon, 75 ft, July 30, 1946

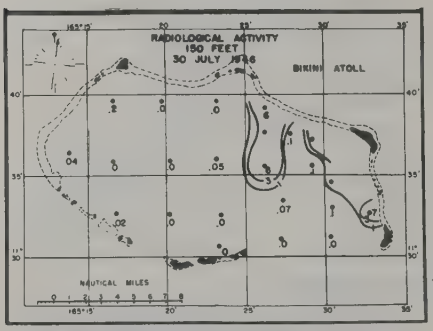

Fig. 21--Radiological activity in Bikini Lagoon, 150 ft, July 30, 1946

The region of upwelling during this period differed in a significant manner from the the norm. VON ARX [1948] reported that the normal zone of upwelling extends from the northern tip of Bikini Island to the southern tip of Enyu Island, having a width of 2400 yd opposite Rokar Island and 3300 yd behind Bikini and Enyu Islands. According to the distribution of radiological activity, the zone had widened at Bikini to more than 6000 yd with perhaps some reduction in width at Enyu. This shift of the upwelling zone may be considered a result of the Enyu Current sweeping into the southern part of the Lagoon and thus deflecting to the north the wind-driven westerly set (which was weak at this time) of the surface lagoon circulation. The model experiments referred to above also showed a similar shift of the upwelling zone.

The development of a slow spiralling action of the water mass in the lee of Bikini Island and the northeast reef would appear to be associated with the widening of the upwelling zone. Such a spiral would explain the persistence of the high but dwindling activity counts in that area, and would provide a mechanism for the feeding of radioactive water out to the west. The existence of a spiral in the lee of Bikini was also indicated by direct current measurements made during the occurrence of a southeast wind before Baker Day, and by model experiments referred to above. The changes in the salinity distribution patterns from July 28 to 30, already discussed, confirm the existence of upwelling and a current along the east and northeast reefs, but they did not indicate the spiral nature of the current.

On considering the distribution patterns of both salinity and activity for July 30 with a view to extending the circulation diagram west from the Bikini sprial, a complex situation located in the north-central part of the Lagoon is encountered. This area was characterized by a persistent surface layer of relatively high salinity. On July 28, it was of large extent and contained water with salinity greater than 34.60 $^{o}/_{oo}$ (see Fig. 3). As a result of the intrusion of ocean water through Enyu Channel on July 29, it was displaced to the northeast and somewhat diluted (see Fig. 4). This displacement is also shown in the activity patterns for these two days (see Fig. 13 and 16). On July 30, the water of higher salinity had returned to about its position on July 28, thus indicating the presence of a westerly drift of the surface waters. This is in agreement with the westerly movement of activity shown by Figures 16 and 19 for this area. However, the persistence of the higher salinity indicates the existence of a slow eddy system in the north-central section of the Lagoon shown in Figure 22. Evidence for such a system in that area was also shown by the model experiments.

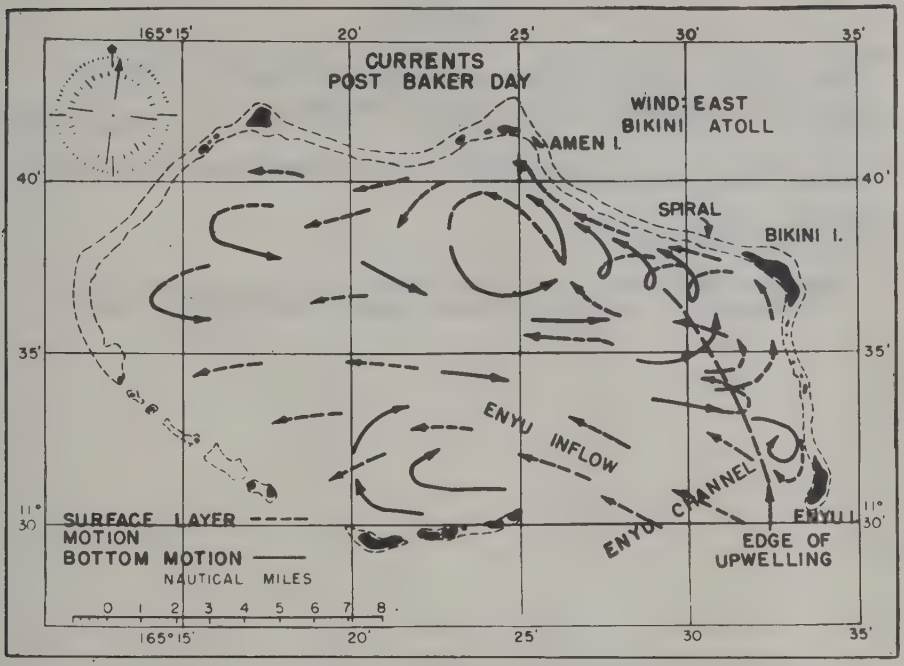

Fig. 22--General features of the currents in Bikini Lagoon as of July 30, 1946

Conclusions--The abnormal circulation of the waters of Bikini Lagoon during the several days following the underwater atomic blast has been described in some detail and with particular reference to the movement and areas of concentration of radioactive material. It is felt that this may be of value in studies of the effect of radiological contamination on the marine flora and fauna, especially the sedentary forms, at Bikini.

It has been demonstrated that the determination of radioactivity distribution in a water mass repeated at various intervals after the activity has been introduced into the system can give valuable information as to the circulation. This radioactive tracer technique in general resembles the conventional salinity method but has the considerable advantage that the activity may be put into the water at strategically selected points, either all at once, giving a zone of high concentration which will diffuse out as it moves with the water mass; or continuously, thus producing a fixed source of activity. It may be argued that the use of radioactive tracers as a general hydrographic tool would not be practical because of the danger of serious contamination of marine life in the areas to be investigated. Though all the ramifications of this question are beyond the scope of this paper, it can be pointed out that the concentrations of activity required are very small, being limited chiefly by the background count. There are certain other obvious limitations. The method would be confined to the study of relatively small areas, the size of which would depend upon the amount of radioactive material available or safely usable. Only those radioactive compounds which would not be involved in biological processes to a significant degree could be used. If, for example, radioactive phosphorus as a soluble phosphate were to be used in quantities suitable for use as a radioactive tracer of a water circulation, it would be at levels of concentration comparable to the normal range of phosphorus in the sea [0.0 to 3.0 microgram atoms per liter, SVERDRUP, JOHNSON, and FLEMING, 1942, p. 241] and would therefore be subject to removal from solution by biological activity.

Acknowledgment--The radiological data presented here were made available to the author through the kindness of K. G. Scott and Gifford Ewing following release by the The Commander, Joint Task Force One (Operation Crossroads).

References

KNUDSEN, MARTIN, The determination of chlorinity by the Knudsen Method; a translation of Chloruration par la méthode de Knudsen, by MIECZYSLAW OXNER, with a reprint of hydrographical tables; Woods Hole Oceanographic Inst., 1946.

SVERDRUP, H. U.; JOHNSON, M. W.; and FLEMING, R. H., The oceans, Prentice-Hall, New York, 1942.

VON ARX, WILLIAM S., The circulation systems of Bikini and Rongelap Lagoons, Trans. Amer. Geophys. Union, v. 29, pp. 861-870, 1948.

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(Manuscript received July 19, 1948; presented at the Twenty-Eighth Annual Meeting, Washington, D. C., April 28, 1947; open for formal discussion until July 1, 1949.)

Contribution No. 435

Made in United States of America

Reprinted from Annals of The New York Academy of Sciences
Volume 51, Art. 3, Pages 483–501, May, 1949

SEA SURFACE ROUGHNESS MEASUREMENTS IN THEORY AND PRACTICE

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Introduction. Although the physical characteristics of the sea surface have influenced the economy and livelihood of a large percentage of mankind, it is a subject which has rarely been investigated systematically. It is perhaps no exaggeration to state that catastrophic conditions of the sea have claimed as many lives and destroyed as much property as any other geophysical phenomenon. However, regardless of its hazardous history, the sea surface is often regarded with a sort of mysticism as a natural phenomenon to be gambled with, rather than approached in an orderly systematic fashion. To some extent, a disinterested attitude toward marine scientific investigations has arisen from an absence of ocean-mindedness and from a false security of this country's isolation by the world's oceans. Thus, industries frequently proceed from the standpoint of overcoming the natural forces of the ocean, rather than approaching them in a harmonious manner.

The basic need in a general wave research program is systematic and accurate observations on the state of the sea surface. The present status of wave research is somewhat analogous to that of oceanic circulation a half century ago. At that time, there had been various special theoretical and experimental treatments of the distributions of mass in the sea, but supported by inadequate field observations. It was not until the relatively recent compilations of basic temperature and salinity observations and their subsequent analyses, that definite progress has been made in the interpretation of the ocean environment. Direct observations of the phenomena are essential to indicate the direction of theoretical research and to bring out new fields of investigation which ultimately become of practical importance.

Our present knowledge of sea surface wave characteristics is far from adequate to solve problems of practical significance. For instance, reliable witnesses have on occasions reported seas as being in excess of fifty feet in height from crest to trough, and the literature suggests fantastic sea conditions in the regions of tropical storms. On the other side of the ledger, it is of interest to note that the highest wave measured by the German research ship "METEOR," during three continuous years in the South Atlantic ocean, was about thirty feet.[1] These and other scientific observations suggest that reported wave heights are frequently exaggerated. The visual observations of individuals under duress do not have a high degree of reliability and the combination of wave frequency, steepness, and height contribute to an illusion of height alone. For instance, the coastal seas of New

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England are notorious for roughness conditions during the fall and winter seasons. The wave heights automatically recorded during the autumn of 1946 show that wave heights are not as great as may be inferred, and that combinations of wave height and wave frequency produce roughness conditions rather than wave height alone. Analyses of sea surface conditions in the vicinity of Woods Hole, during the autumn of 1946, show the most frequently occurring wave height to be of less than one foot, and an average wave height of 2.3 feet. Fifty per cent of the time the highest waves occurring in twenty minute sequences were less than three feet, and ninety-five per cent of the time less than fifteen feet.

Sea Surface Roughness and Military Operations

The absence of concrete data on the physical characteristics of the sea surface have resulted in a general inability to translate sea-surface conditions into operational or design situations, and a vagueness exists as to the limits of sea-surface conditions for operating various types of surface craft, as well as for other phases of maritime activity. In particular, this was brought into prominence by amphibious operations of the recent war.[2] Perhaps a clear idea of the situation may be brought out by brief reference to the invasion of the Normandy beaches in June 1944. The heights of waves on the assault beaches had been forecasted on board the Command ship (Ancon), for two days previous to the assault on June 6, and were transmitted directly to the staff of First U. S. Army. Observers on the beach at D-day verified that maximum wave heights in the off-shore debarking areas, and of surf on the target beaches, did not, in general, exceed 4 feet, as forecasted. Hence, the difficulties in carrying out the invasion plan because of adverse sea conditions were not the result of inadequate or erroneous advance information, but rather an inability to associate sea conditions to the details of the plan itself. In particular, sea conditions interfered with the timing of transfer of men and materiel from transports to small assault craft in the off-shore debarking areas, and in the eventual time and locations of landings on the target beaches. The result was that the neatly prepared paper operational schedule broke down in practice. It is known that, for instance, infantry units committed to build up firing lines on the beaches actually arrived off schedule and took shelter among the enemy beach obstacles, in process of being cleared by engineer demolition teams. The cost in loss of life and materiel was excessive.

A second example of a catastrophe during this military operation, which resulted from lack of adequate design to meet sea conditions, concerns the destruction of the artificial harbors and causeways off the Normandy coast during the storm June 19–20, 1944. These artificial structures had been erected, at great difficulty and expense, for the purpose of providing shelter for small surface craft engaged in the transferring of cargo from ship to shore during the critical period of the operation. However, it so happened that

two weeks after the initial assault, and at a time when the supply of American forces was critical, the installation was thoroughly destroyed by a storm. The loss of these structures seriously handicapped the continental military operations.

It has become apparent to even the uninitiated that inadequate information on surface conditions played a costly role in amphibious operations of the recent war. Reports of military operations in coastal areas, now almost invariably decry the lack of adequate prelanding information, and, in general, the effects of sea-surface conditions on all phases of the operation had to be learned in the field—usually under adverse conditions.[3]

From June to November of 1944, at the time cargo and personnel were being transferred from ships anchored off shore to the open Normandy beaches, a local state of the sea forecasting service was in operation under the direction of the European Theater Military Oceanographer.* Some time after cargo operations had become stabilized, it was evident that the forecasting of impending sea conditions could be prepared in terms of the actual operation, that is, in terms of the feasibility of DUKWS and coasters to operate from transports to shore.

FIGURE 1 illustrates the actual relationship of maximum cargo unloadings in relation to height of surf on the Normandy beaches during October, 1944. By using maximum values, tonnage drops resulting from delays in assembling craft and other uncontrollable factors are eliminated. During October, the available arrangement and equipment was such that, under favorable conditions, a maximum of 10,000 long tons could be discharged daily. Thus, FIGURE 1 shows that surf heights up to one and one-half feet did not interfere with this maximum capacity. With greater surf height, cargo operations became difficult and for surf heights of three and a half feet the unloadings were reduced to about fifty-five per cent of the possible total. Surf heights between three and a half and four feet were critical. For the latter, total cargo unloadings of only twenty per cent efficiency were possible. Above four feet, operations were impaired so severely that the high maintenance costs were justified only in cases where the supply of inland armies was critical. At six feet surf height, all cargo operations were forced to cease regardless of demand.

The above simple relationship represents one of those things which, if it had been available during the planning stages of the Normandy operation, would have eliminated much of the guesswork and confusion regarding the supply of our inland armies. As it was, the initial elaborate plans for restoring ports and harbors were later dismissed in favor of maintaining cargo operations across the original Normandy beaches until the beginning of winter—something not thought possible before the invasion.

These brief references to the military aspects of this picture are given

* This author, Lt. Col., Corps of Engineer Reserve. Then commanding 6812 Engineer Technical Intelligence Team.

because of the writer's practical acquaintance with the examples and because the results drive home the need for investigation of sea-surface characteristics. When human lives are at stake, a high priority should be given to the investigation of those phenomena which have so clearly been demonstrated as controlling factors.

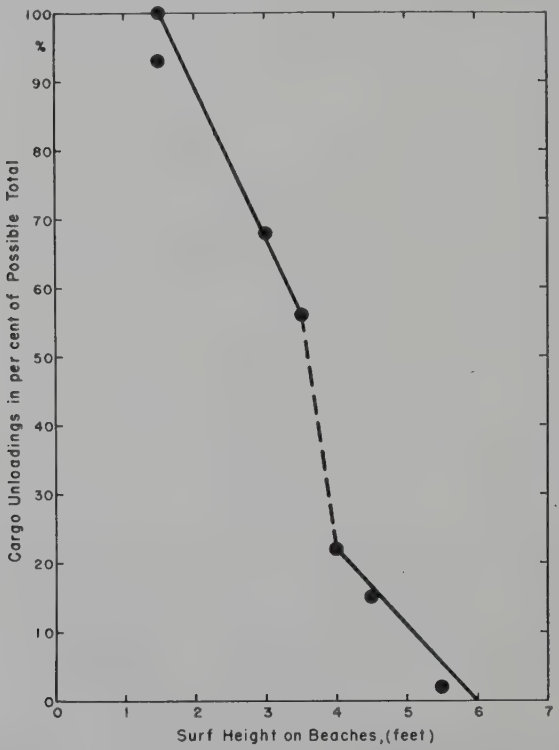


FIGURE 1. Observed relationships between surf heights and maximum daily tonnage discharged, Omaha Beach, Normandy, France, October 1 to 28, 1944. Drawn from data in Figure 2 "Military Oceanography in World War II."[2]

Methods for Measuring Sea Surface Roughness Conditions

Roughness conditions of the sea surface may be measured by three general methods, all of which were developed as a result of wartime oceanographic research. These are: (1) By matched pairs of overlapping vertical photographs projected in stereo; (2) By evaluation of the state of the sea surface from wind patterns of past weather maps; (3) By automatic recording of pressure variations near the sea bottom.

The first method requires the use of specially equipped aircraft, including a mounted continuous strip Sonne Stereo Camera and a radio altimeter, to be operated by a trained pilot. Skilled interpretations of the resulting photographs are also necessary. This method, used with varying degrees of success during the war, served as an excellent check on trial forecasts of sea and swell.

The method of determining sea surface roughness conditions from wind distributions over the ocean is the simplest and most rapid approach to the problem[4]. It is limited, however, by the uncertainty of empirical relationships between wind and sea, as well as by uncertainties in computed wind distribution patterns over the open oceans. Later, when empirical relationships of wind and sea are better established, this method will probably be of top priority.

The method of evaluating sea-surface conditions from automatic recordings of pressure variations near the sea bottom has been in use at the Woods Hole Oceanographic and other institutions. The instruments in use are discussed by the builder A. A. Klebba.[5] In my opinion, this method is, for the present, the most satisfactory available to provide urgently required basic data. Theoretically, the method is limited to the recording of pressure pulses of surface waves whose lengths exceed approximately twice the depth of instrumentation. However, regardless of this, the judicious installation of automatic underwater pressure recorders should have a high priority in that they are the only present means for providing state-of-the-sea-surface data under all conditions.

To the above methods should be added one involving photographic recording of wave heights against a graduated pole, either anchored to the sea bottom or in the deep ocean, held in place by means of a deep baffle extending toward the downward limit of wave action. Motion-picture recordings of the wave profiles are later scaled for wave height and wave period. This method has been successfully used in water up to 125 feet deep by this institution, and during the present cruise of the ATLANTIS wave recordings are being made by the above deep-water method. The exact details of the ATLANTIS apparatus are not known, as it has undergone some modifications while at sea. Essentially, it consists of a 30 foot pole, graduated in alternate black and white stripes, to which a long baffle is attached. After the pole is set adrift, timed photographic recordings on 16-millimeter film are made for 90-second intervals. Some recent results, obtained from the recordings in the North Atlantic are illustrated by FIGURE 2. These data will be later analyzed with reference to prevailing wind distributions.

Some Significant Results of Sea Surface Roughness Measurements

The remainder of this paper is concerned with certain analytical results of sea surface wave data obtained from evaluations of underwater pressure instrument records, in order to review briefly some pertinent results to be

obtained from this type of information. The pressure-measuring elements were located, one off Cuttyhunk Island at a depth of 75 feet, and the other off Bermuda, at a depth of 120 feet (FIGURE 3). In both cases, they were connected to onshore recorders several miles away. Because of installation locations, pressure pulses of wave lengths less than 150 feet at Cuttyhunk and less than 240 feet at Bermuda were not expected to be recorded. The operational schedule of the Cuttyhunk instrument, from July, 1946, to May,

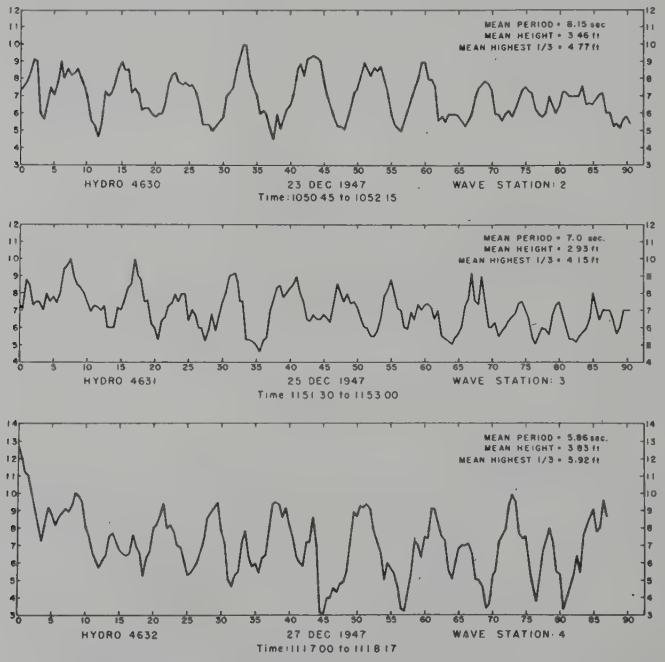

MEAN PERIOD = 8.15 sec
MEAN HEIGHT = 3.46 ft
MEAN HIGHEST 1/3 = 4.77 ft
HYDRO 4630
23 DEC 1947
WAVE STATION: 2
Time: 1050 45 to 1052 15
MEAN PERIOD = 7.0 sec.
MEAN HEIGHT = 2.93 ft
MEAN HIGHEST 1/3 = 4.15 ft
HYDRO 4631
25 DEC 1947
WAVE STATION: 3
Time 1151 30 to 1153 00
MEAN PERIOD = 5.86 sec.
MEAN HEIGHT = 3.83 ft
MEAN HIGHEST 1/3 = 5.92 ft
HYDRO 4632
27 DEC 1947
WAVE STATION: 4
Time: 1117 00 to 1118 17

FIGURE 2. Results of measurements of sea surface roughness in the North Atlantic during ATLANTIS winter cruise, December, 1947.

1947, was a continuous 20-minute recording every 6 hours; that at Bermuda, from February, 1947, to May, 1947, a continuous 20-minute recording every 2 hours. The records (FIGURE 4) were scaled for pressure wave heights and evaluated in terms of wave heights at the physical sea surface immediately overhead.

Because with surface waves the downward acceleration of the water particles below the crest counteracts the effect of gravity, and the upward acceleration of those below the trough adds to it, pressures are not perceptible at depths where orbital motion is imperceptible, regardless of surface wave

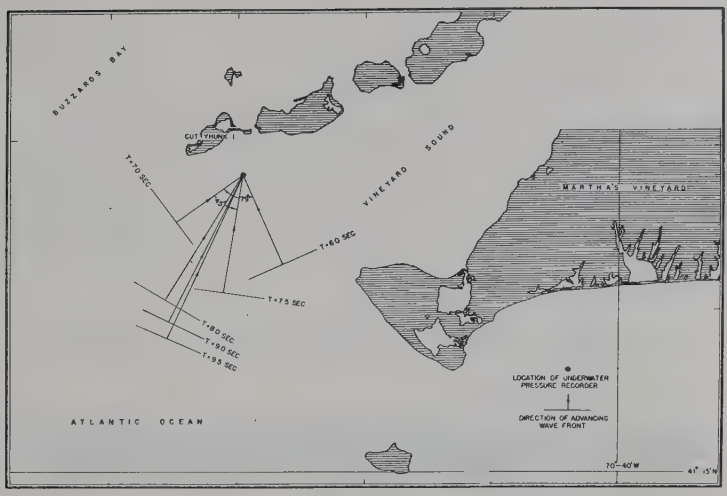


FIGURE 3a.

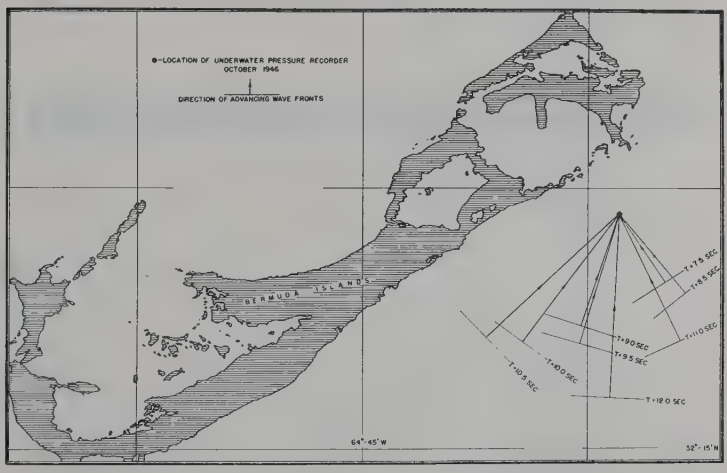


FIGURE 3b.

Locations of underwater pressure wave recorders at Cuttyhunk (3a) and Bermuda (3b). Directions of advancing surface wave fronts computed from differences in surface and bottom phase angles of wave components, as obtained from experimental observations on 27 June, 1946 at Cuttyhunk, and 25 October, 1946 at Bermuda.[6]

heights. Theoretically, the relation between surface (ΔP_s) and bottom (ΔP_h) pressure fluctuations (at depth h) is given by:[6]

$$\frac{\Delta P_h}{\Delta P_s} = \frac{1}{\cosh kh}$$

where

$$k = \frac{2\pi}{\text{wave length}}.$$

The damping phenomenon is, thus, selective to the extent that longer period waves, frequently obscured at the sea surface, are generally recognizable in underwater pressure records. By the same token, shorter wave lengths, which do not exceed approximately twice the depth of instrumentation, are not recorded, regardless of their height. This fact calls for a judicious selection of instrument sites, when measuring surface waves by the method of bottom pressure fluctuations.

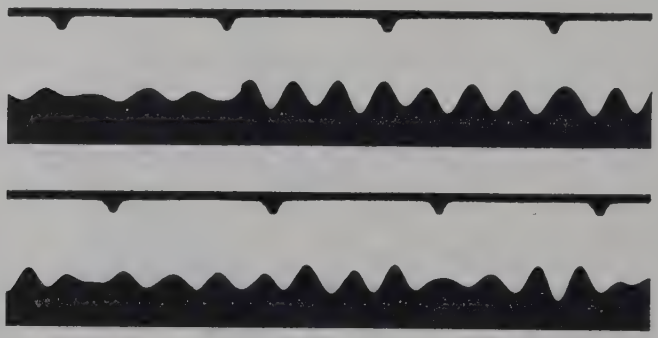


FIGURE 4. Reproductions from parts of two underwater pressure wave records obtained from the Cuttyhunk location on 14 June, 1946. Time ticks are for thirty-second intervals. Bottom wave heights computed from instrument factors and evaluated in terms of surface wave heights as described in text.

The results given by the above equation are not in complete agreement with observations, hence the possibility must not be overlooked that other solutions may be discovered to satisfy the observed conditions. With this in view, a series of experiments was performed at both Bermuda and Cuttyhunk, whereby wave heights of the physical sea surface immediately overhead the underwater pressure records were photographically recorded for comparison with wave heights computed from instrument recordings by theory. It was found that, for both localities, better representations of sea-surface conditions were obtained when theoretical results were multiplied by a factor of 1.35. This factor is accepted only for the localities involved. It is doubtful, in view of the complex variations of natural conditions, if a universal factor is possible and, for the present, empirical relationships need be established for each locality from experiments in the field. Eventually, with accumulation of field results, other solutions will be discovered to modify existing wave theory so as to better satisfy observed conditions.

In this connection, it is of interest to point out that many instances in the

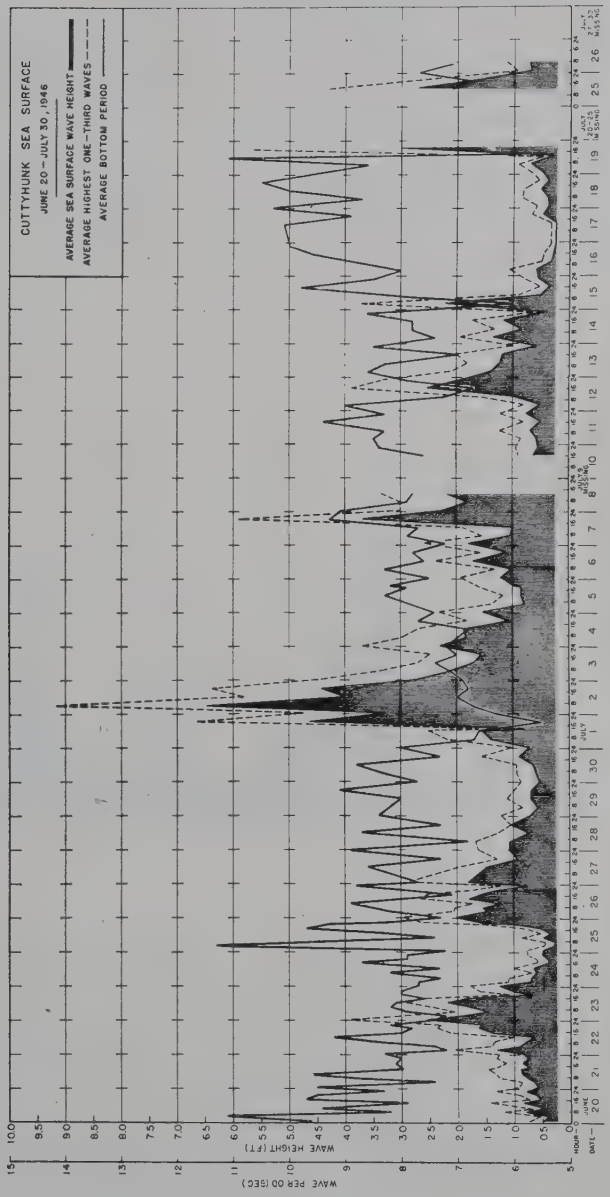


FIGURE 5. The state of the sea surface off Cuttyhunk Island, June 20 to July 30, 1946, as computed from six-hourly underwater pressure recordings.

literature show observed conditions of wave action in coastal areas do not fit within the framework of existing shallow-water wave theory. During the war, it was particularly apparent to those engaged in producing reconnaissance intelligence that theoretical reductions of wave observations were not compatible with existing conditions. A specific example is the determination of underwater depths from measured changes in the wave patterns of aerial photographs. Almost invariably, it was necessary to introduce empirical factors to take up discrepancies between computed and theoretical

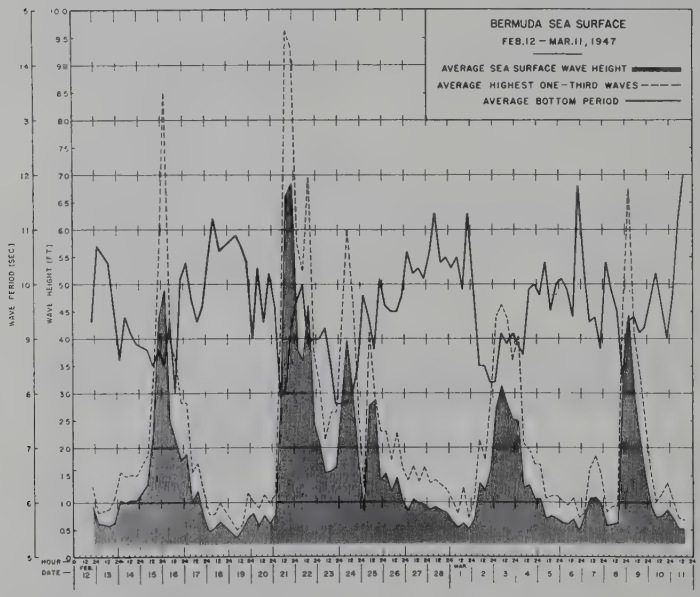


FIGURE 6. The state of the sea surface off Bermuda, February 12 to March 11, 1947, as computed from two-hourly underwater pressure recordings.

values. However, the basis for the revision of present wave theory and for the discovery of more suitable solutions depends on obtaining accurate observations on the state of the sea surface itself.

Examples of sea surface wave characteristics[6] at Cuttyhunk from June 20 to July 30, 1946, and for Bermuda from February 12 to March 11, 1947, are illustrated by FIGURES 5 and 6. In these figures, average six-hourly sea surface wave heights, average highest one-third waves, and average bottom periods are shown. These data, when arranged in suitable frequency distributions and subjected to standard statistical procedures, provide information on sea-surface characteristics at the two localities considered. The

prognostic usefulness is dependent on the extent to which the data are characteristic of usual prevailing conditions.

TABLE 1 summarizes the seasonal statistical properties of sea surface roughness conditions at Cuttyhunk and Bermuda, based on analyses of more than 1600 twenty-minute records. The data show that seasonal changes in the state of the sea are reflected in the extreme, rather than in the mean conditions. Thus, at Cuttyhunk, while the mean wave height increased from 1.3 feet in summer to 2.3 feet in autumn, the heights of the highest waves increased from 16 to 22 feet. At Bermuda, the situation was similar. Mean wave height diminished from 1.7 feet in winter to 0.8 feet in spring,

TABLE 1

STATISTICAL SUMMARY OF SEASONAL SEA SURFACE PROPERTIES FOR CUTTYHUNK AND BERMUDA*

Season	*Mean Wave Height*					*Maximum Wave Height*			*Mean Wave Period*		
		Mode	*P.E.*	*Occurrence below mode*	*Variability*	*50 per cent occurrence*	*95 per cent occurrence*	*Highest wave*	*Mean*	*Mode*	*P.E.*
					Cuttyhunk Wave Station						
Spring	1.3	0.6	0.1	41	.81	to 2.8	to 9.0	16	8.6	7.9	0.2
Summer	1.3	0.7	0.1	48	.80	to 2.5	to 9.5	15	8.4	(8.3)	0.1
Autumn	2.3	0.9	0.1	39	.83	to 2.9	to 14.5	22	8.1	6.8	0.1
					Bermuda Wave Station						
Winter	1.7	0.8	0.1	42	0.81	to 2.8	to 10.5	17	9.6	9.5	0.1
Spring	0.8	0.7	0.02	62	0.52	to 2.3	to 4.5	7	10.1	9.3	0.1

* Statistical summary of seasonal characteristics of sea surface roughness at Cuttyhunk and Bermuda, computed from recordings of underwater pressure fluctuations. Wave heights in feet; periods in seconds; occurence figures in per cent.

and the maximum wave heights from 17 to 7 feet. Results such as these permit estimates of expected regional operational conditions.

The Growth and Decay of the Sea Surface

An ideal solution to the practical problem of sea surface roughness would be one establishing statistical relationships between rates of change of sea surface wave heights and wave periods and the prevailing state of the sea. The data available do not permit this extensive analysis, in that the relatively few months comprise only single series of observations. Consequently, our results are valid only in so far as the single series of observations conform to near normal values for the months in question.

The rates of change of wave heights were computed from the Cuttyhunk six-hourly and the Bermuda two-hourly records. In treating the general case, frequency distributions for the separate positive and negative rates of

change at each locality were formed. The statistical quantities describing them are tabulated in TABLE 2.

The situation demonstrated by TABLE 2 indicates a remarkable uniformity in rates of growth and decay of sea-surface roughness. Both are about equal, with an overall range up to 1.9 feet per hour. The most frequently occurring changes in sea surface wave heights are very small, about 0.05 feet per hour, occurring about 30 per cent of the time. Rates of change of sea surface wave heights occurring 50 per cent of the time do not exceed 0.12 feet per hour, and 75 per cent of the time do not exceed 0.25 feet per hour. At both localities, sea surface wave heights increased and diminished at approximately the same average rate, namely 0.17 feet per hour. The rates of change of sea surface wave height in excess of one foot per hour occur less than 2 per cent of the time. It is apparent that only in exceptional cases does the state of the sea surface roughness change rapidly.

TABLE 2*

	Cuttyhunk		*Bermuda*	
	$+\frac{\Delta H}{\Delta t}$	$-\frac{\Delta H}{\Delta t}$	$+\frac{\Delta H}{\Delta t}$	$-\frac{\Delta H}{\Delta t}$
Mean	0.16	0.14	0.18	0.20
Mode	0.05	0.05	0.05	0.05
Probable error	0.01	0.01	0.01	0.01
50 per cent occurrence	to 0.08	to 0.08	to 0.10	to 0.12
75 per cent occurrence	to 0.19	to 0.17	to 0.20	to 0.25
Maximum value	1.5	1.5	1.9	1.9

* Statistical summary of rates of change of wave height ($+\Delta H/\Delta t$ = increasing; $-\Delta H/\Delta t$ = decreasing, feet per hour) for Cuttyhunk (July 1946 to May 1947) and Bermuda (February 1947 to May 1947).

Interrelationships of Wave Characteristics

A study of the data has brought out that, at both Cuttyhunk and Bermuda, higher wave heights are generally accompanied by lower wave periods and vice versa. Thus, at the former locality TABLE 1, we see that increased mean wave heights from 1.3 feet in spring to 2.3 feet in autumn is accompanied by diminished mean wave periods, from 8.6 to 8.1 seconds. Similarly, at Bermuda, where mean wave height diminished from 1.7 feet in winter to 0.8 feet in spring, the accompanying mean wave period increased from 9.6 to 10.1 seconds. This is the observed overall pattern. With the exception of occasional departures, higher surface wave heights and wave periods are similarly related. Thus, FIGURE 7 shows that relationships between rates of change in wave height and wave period, as derived by least square fits, are as follows:

for Cuttyhunk $$\frac{\Delta H}{\Delta t} = -0.42\,\frac{\Delta T}{\Delta t},$$

for Bermuda $$\frac{\Delta H}{\Delta t} = -0.26\,\frac{\Delta T}{\Delta t}.$$

The Determination of Operational Wave Heights from Average Wave Heights

The situations discussed so far are based on mean wave heights for 2-minute intervals every 2 or 6 hours, as the case may be. Coincident with the computation of mean wave heights, the means of the highest one-third surface waves were also determined for each record. These latter values are termed "operational wave heights," in that they better represent practical effects of sea surface roughness conditions than do mean values for all wave heights. The deduction is arbitrary, but from the standpoint of practical operations a somewhat better index of sea surface roughness conditions is provided.

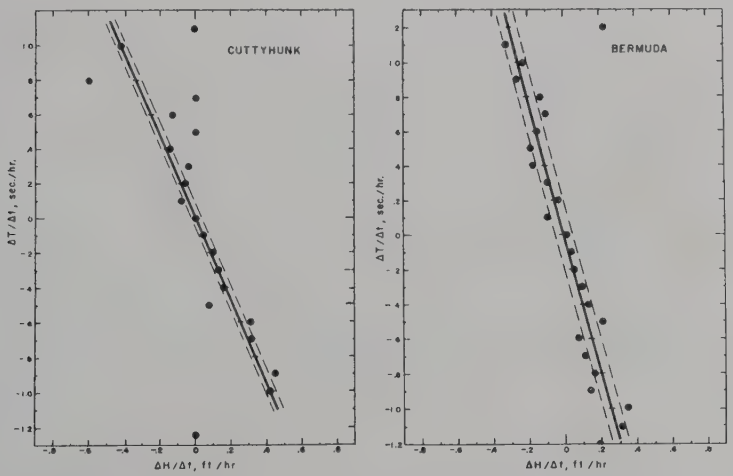


FIGURE 7. Relationships between the rates of change of wave periods and wave heights for Cuttyhunk and Bermuda.

The data from both Bermuda and Cuttyhunk show a significant relationship between the average of all wave heights and the averages of the highest one-third wave heights. This is illustrated for Cuttyhunk (639 observations) and for Bermuda (1022 observations) by FIGURE 8. Independent fits of straight lines by least squares to both sets of data give identical results, thus:

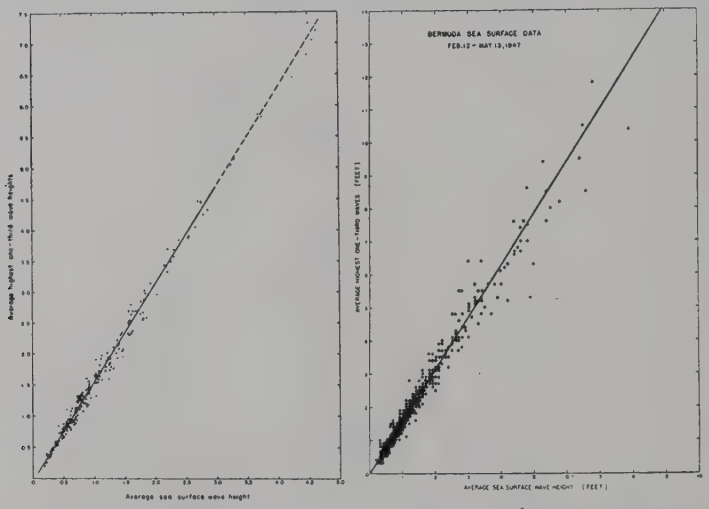
$$\text{Mean of highest one-third waves} = 1.57 \times \text{mean wave height.}$$

Hence, it is reasonable to compute operational wave heights by multiplying the mean of all wave heights by the factor 1.57. However, as for other factors derived in this study, they are, for the present, considered pertinent only for the localities for which derived. It is considered too early to generalize on the meager results of this and similar investigations.

These and other interrelationships of sea surface wave characteristics

contribute to an understanding of the complex sea surface patterns, as well as indicating regularities of practical significance within the patterns themselves. The few examples demonstrate that adequate field observations of the sea surface, when subjected to statistical analyses, will provide answers to many practical questions, as well as point the way to one phase of theoretical research on the sea surface.

As a final example, a functional method for evaluating operational sea surface conditions for any locality and for contrasting these conditions over


Average highest one-third wave heights
Average sea surface wave height
BERMUDA SEA SURFACE DATA
FEB. 12 - MAY 13, 1947
AVERAGE HIGHEST ONE-THIRD WAVES (FEET)
AVERAGE SEA SURFACE WAVE HEIGHT (FEET)

a. b.

FIGURE 8. Relationship of average sea surface wave heights and average heights of highest one-third surface waves for Cuttyhunk (8a) and Bermuda (8b). The independent fits of straight lines by least squares to both sets of data give identical results, thus: *Mean of highest one-third waves = 1.57 × mean wave height.*

the world's oceans is outlined. Since its development depends on available sea surface data its present use is restricted to a few oceanic localities.

From a practical standpoint, operational conditions of the sea surface may be considered as a function of wave height and wave period. Thus, in regions of permanently restricted fetch (as the English Channel), there is far less variability in operational conditions than in an area such as the Eastern American coast, where all wave frequencies within the wind generating band are possible. A representation of operational conditions by combinations of wave height and wave period for the waters in the vicinity of Woods Hole, during the summer of 1946, is shown by FIGURE 9. In this example, the various combinations of operational wave heights and wave periods into favorable, unfavorable, and conditional situations are with reference to small-boat work. The division is arbitrary and presented pri-

marily from the standpoint of a method. The boundaries of wave height-wave period combinations may be selected with reference to any type of operation on the basis of experience. Each figure in Part A, FIGURE 9, represents the per cent occurrence of the wave height-wave period combina-

PART A

WAVE HEIGHT	WAVE PERIODS 5-6	6-7	7-8	8-9	9-10	10-11	11-12	PERCENT SUMMARY
10-11		0.4						0.4
9-10								
8-9	0.4							0.4
7-8	0.9	1.8	0.4					3.1
6-7		0.8						0.8
5-6	0.5	1.8			0.4			2.7
4-5	0.4	2.3	1.7					4.4
3-4	0.4	1.4	4.9	0.9	0.5			8.1
2-3		3.5	10.7	3.6	0.4			18.2
1-2		1.8	18.7	12.5	3.6	0.4		37.0
0-1			4.4	8.4	8.9	1.9	1.3	24.9
PERCENT SUMMARY	2.6	13.8	40.3	25.4	13.3	2.2	1.3	100

Summary Sea Surface operating conditions in Percent of Time, Cuttyhunk, Summer 1946. Wave height (feet) = average highest one third wave during twenty minute intervals. Wave period (seconds) = average recorded at bottom. Small boat operating conditions: Favorable; bounded by solid lines; unfavorable; bounded by dashed lines.

PART B

LOCATION	SEASON	SEA SURFACE CONDITION Favorable	Unfavorable	Intermediate
CUTTYHUNK	Spring	73	13	14
	Summer	77	12	11
	Autumn	55	31	14
BERMUDA	Winter	74	11	15
	Spring	90	1	9

Summary Sea Surface seasonal operating conditions in Percent of Time at Cuttyhunk and Bermuda as computed from boundaries established in Part A.

FIGURE 9.

tion. Summing values within these arbitrarily selected zones gives the following estimate of summer operating conditions: favorable, unfavorable, and intermediate operating conditions, 77, 12, and 11 per cent, respectively.

The extension of this scheme to the summer and autumn seasons for Cuttyhunk and the winter and spring seasons for Bermuda, produces the seasonal operational summary of Part B, FIGURE 9. This enables a comparison

of seasonal operational conditions, within defined boundaries. It shows that, for the Woods Hole region, the 75 per cent favorable operating conditions of spring and summer are reduced to about 50 per cent during the autumn. At Bermuda, the 75 per cent favorable operating conditions in winter increase to 90 per cent in spring. If the data were available, similar schedules for any type of marine operation could be established throughout the world, and much of the guesswork now characterizing operations of this type would be eliminated.

TABLE 3*

	Cuttyhunk			*Bermuda*	
	Spring	*Summer*	*Autumn*	*Winter*	*Spring*
Wave height					
Mean	2.0	2.2	3.7	2.6	1.3
Mode	0.9	1.2	1.4	1.2	1.1
Maximum	16	15	22	17	7
Wave length					
Mean	381	365	337	472	520
Mode	325	360	233	461	444
Maximum	832	900	832	1040	1040
Wave velocity					
Mean	26.0	25.5	24.5	29.1	30.6
Mode	24.0	25.3	20.5	28.8	28.2
Maximum	38.6	40.2	38.6	43.2	43.2
Wave steepness					
Mean	.54	.65	1.16	.55	.25
Mode	.28	.34	.61	.27	.25
Maximum	8.7	8.2	12.0	9.2	3.8

* Summary of seasonal sea surface properties for Cuttyhunk and Bermuda computed from basic observational data. Wave heights, (feet) = averages of highest one-third waves. Wave length (feet) = 5.12 × (period)^2. Wave velocity (knots) = 3.03 × (period). Wave steepness (per cent) = wave height/wave length; maximum values computed for six-second periods.

Sea Surface Roughness Factors in Relation to Design

So far, this discussion has been concerned with operational results of sea-surface analyses. However, the same basic data from which they have been derived also lend themselves to computations of the forces of waves and inertia exerted on the hulls of surface craft and fixed marine structures. These computations are of practical importance to the designer of surface craft and marine structures, although a closer coordination between the oceanographer and the marine designer is needed to bring out their full significance. "There is a fundamental difference in the analyses of data, in that, from an operation standpoint, emphases are placed on the mean or average conditions, whereas for design, the maximum or extreme conditions play the prominent role.

A computation summary of some relevant sea-surface properties significant to marine structure design is given in TABLE 3. They serve as examples

of what may be computed from the basic data. For the region under consideration, it is of interest that the shorter and higher seas of fall and winter produce greater steepness values than at other times of the year. The maximum steepness values, although occurring rarely, are, for waves of 800 to 1000 feet long, greater than generally allowed for in the stress computations of marine craft design. The maximum wave lengths recorded are about three times greater than those most usually occurring.

Conclusions

Although observations on oceanic phenomena have been recorded since the dawn of history, the systematic investigation of the oceans is a young science. Some of the branches of oceanography, such as coastal tides and tidal currents have, because of their practical importance, been placed on a systematic basis years ago, and, as a consequence, are further advanced in both theory and practice. As far as sea surface waves are concerned, the numerous visual and often sporadic observations made from ships at sea have been useful for past objectives in providing pictures of general situations, but are for the most part not usable for the precise analyses now required for present operational and design trends. This was realized during the war, when the practical problems of military oceanography called for development of special wave recording instruments, as well as for special wave studies. With this impetus given to wave research, we have come a long way in our knowledge of sea-surface characteristics, and are in a position to formulate new lines of research pertinent to both scientific investigation and industry. In addition, there is the benefit to problems arising in connection with the future defense of this country, it being significant that the historical inference of security from oceanic isolation is now no longer correct. The environmental problems of new types of coastal installations and the maintenance of world-wide lines of rapid communication add to the necessity for a program aimed at understanding the characteristics of the sea-surface layers. The knowledge gained from investigations of the last war is no longer adequate to present peacetime problems of either science or industry, because neither has stagnated.

The practical application of results of wave research and the expansion of this phase of oceanography call for a closer coordination and cooperation between the oceanographer and the engineers and production personnel of industry. The separation in duties of the personnel involved requires that industry be advised by oceanographers with backgrounds of research, so they can envision future lines of research and not permit a stagnation at present levels. To keep abreast of an advancing science, the expansion of present oceanographic research facilities and personnel, such as can be accomplished by cooperation with industry, is essential. This requires bringing to the attention of industry such of the numerous present and future uses of results of oceanographic research as benefit their economy.

Sea surface wave research is an oceanographic subject which has been brought into the limelight as of great practical importance. It now remains to formulate adequately the scientific and practical problems to support a continuing progress. This paper has been concerned only with the practical analyses of results of field observations. From this viewpoint, the primary requirement is establishment, in the not too distant future, of a controlled program of field observations, located at strategic places throughout the world's oceans. As the results of such analyses become available, we approach a position enabling us to forecast and provide prognosis for areas where direct observations are obtained only with extreme difficulty, and where, as has been demonstrated in the past, they will undoubtedly be required in the event of another world emergency.

Bibliography

1. Schumacher, A. 1927. Ozeanographische Sonderuntersuchungen Zeitschrift der Gesellschraft fur Erdkunde zu Berlin. **5/6:** 304–307.
2. Seiwell, H. R. 1947. "Military Oceanography in World War II". The Military Engineer. **39**(259): 202–210.
3. 1945. Omaha Beachhead Historical Division, U. S. War Department.
4. Sverdrup H. U. & W. H. Munk, 1943. Wind waves and swell Principles in forecasting. U. S. Navy Hydro. Off. Misc. Pub. **11:** 275.
5. Klebba, A. A. 1949. Details of Shore Based Wave Recorder and Ocean Wave Analyzer. Ann. N. Y. Acad. Sci. **51**(3): 533–534.
6. Seiwell, H. R. Results of Research on Surface Waves of The Western North Atlantic. (I). Papers in Physical Oceanography and Meteorology. **10**(4).

Discussion of the Paper

Dr. Kenneth S. M. Davidson (*Director, Experimental Towing Tank, Stevens Institute of Technology, Hoboken, N. J.*):

I am interested in the seakeeping qualities of ships. This is a broad subject, and one on which there exists little authoritative information, despite its great age.

It has become increasingly clear to me that much depends upon establishing close ties between research in oceanography and in naval architecture. The naval architect needs to know more about the nature of the sea surface to which ships have to accommodate themselves, and the oceanographer needs to know more about the sea surface for many other reasons as well. It is natural, therefore, that the two should combine forces. They are feeling their way at the present time, and are in the very early exploratory stages of cooperation. The naval architect does not quite know what questions to ask the oceanographer, and the oceanographer does not quite know what questions to ask the naval architect. They do not yet know how to cooperate to mutual advantage.

The naval architect still represents rough water by a single train of regular trochoidal waves. This simplification has worked out fairly well, and, to the extent that there is usually some sort of "predominant" wave train in any actual seaway, as I gather the oceanographers admit, seems to be justified as a first approximation. In any event, it has been put to good use in

studying such things as, for example, the rolling of ships in beam seas. On the other hand, it is obviously inadequate as a basis for a full understanding of even a simple motion of this sort. Consider: the damping in roll of ordinary ships not equipped with mechanical stabilizing devices corresponds to amplification ratios (roll amplitude/maximum wave slope), at resonance, that lie within a range of something like 4 to 20. Now, there is no evidence that an amplification ratio of the order of 20 means an unsafe ship at sea, as would surely be the case if resonant wave encounters persisted for sufficient time to allow the amplitude in roll to build up. Neither is there good quantitative evidence of improvement (or otherwise), if the amplification ratio is materially reduced, by increasing the damping. Evidently, then, the irregularities of actual sea waves must play a big part in determining the rolling behavior of ships.

This is not a very profound conclusion, perhaps, and it has certainly been suspected many times. The question is what might conceivably be done about it. One answer that suggests itself readily enough is to undertake a much more searching dynamic analysis of rolling than has yet been attempted, employing detailed contour maps of the sea surface, perhaps like those of Schumacher (Meteor Expedition). One would want to be sure of using "typical" maps and to have a clear view at the start of their relation to representative weather conditions. This means that the oceanographer probably ought to select them as well as provide them.

There are, of course, other ways of studying rolling, and I do not wish to be understood as recommending this one especially. The point I want to make, is simply, that if anything new is to be learned about rolling, the irregularities of actual sea waves will almost certainly need to be taken into account. There is no doubt in my mind that this is equally true of all other motions of ships in a seaway, as well as of the forces and stresses imposed on the ship structure.

I have dwelt upon the need of the naval architect for detailed information regarding the character of the sea surface in the immediate vicinity of a ship, because recent oceanographic studies seem to have emphasized mainly the overall aspects, like mean dimensions of waves, probabilities of occurrence, etc., and to have paid little attention to detailed aspects like wave configurations. I do not mean to imply that the naval architect is not interested in the overall aspects. He is, but he needs something more. FIGURE 1 of Mr. Seiwell's paper poses the question fairly. By presumption, the curve on this chart will be shifted bodily toward the right as designs are improved. To improve designs will not be easy at best, but it will be much harder unless a better knowledge is gained of operating conditions, in considerable detail.

There is much to be done. As matters stand at present, a free interchange of views between research groups in naval architecture and in oceanography is probably the most important single step that can be taken.

Contribution No. 438

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Reprinted from Annals of The New York Academy of Sciences
Volume 51, Art. 3, Pages 533–544, May, 1949

DETAILS OF SHORE-BASED WAVE RECORDER AND OCEAN WAVE ANALYZER

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Research groups have been interested in measuring waves at some distance from shore. In order that this work might be furthered with minimum loss of time in securing data, we have developed a set of instruments capable of recording waves in depths of water to 150 feet. The actual recording takes place on shore and the pressure pick-up unit is connected by cable.

The installation is self-powered and can operate continuously or be set to record for fixed periods without attention.

The principal parts of the underwater unit are shown in FIGURE 1. This assembly is approximately 18 inches high and the pressure responsive element is the bellows A, in the upper part of the unit. As this is intended to perform under a static pressure of approximately 100 feet of water, it is held in extension by a comparatively stiff spring B. Bellows A forms a closed air path with another (bellows D), which is directly underneath it in the drawing. The second bellows is a relatively weak structure and will reproduce the motions of the first bellows. It can be seen that if a great difference in static pressures occurs, the lower bellows will be forced to the length of its travel. Compensation for changes in static depth and for tides is accomplished by installing a capillary tubing, C, to connect the air inside the bellows to the chamber immediately surrounding the bellows. This consists of a 6-foot length of copper tubing with a bore of approximately 17-thousandths of an inch. The actuating rod from bellows D is connected to move a coil of wire, E, at the lower end of the unit. This coil of wire is placed in a very strong magnetic field and small movements of the coil produce a voltage proportional to the speed of movement of the coil. These voltages would be the first derivative of the displacement taking place. However, it will be shown that the actual displacement is recorded. A two-conductor cable emerges from the unit and is connected to the recorder located on shore.

The principle of the electrical recording element is merely a description of a commercial fluxmeter galvanometer[1]. This is a taut suspension galvanometer which has a small magnet attached to the lower end of the galvanometer coil. The orientation of this small magnet is to oppose the flux leakage caused by the main magnetic assembly. As a signal is applied to the galvanometer, it tends to rotate the coil. In the usual galvanometer, the torque of the suspension will cause an equilibrium position for a given

* Development of the instruments was supported by the Bureau of Ships, Navy Department. The author is indebted to Lawrence A. Thayer and Frank J. Mather for construction and field testing of the equipment.

Contribution No. 438 from the
Woods Hole Oceanographic Institution.

voltage being applied to the galvanometer. In the case of this device, the small magnet is rotated so that a correction torque is applied in the direction of the rotation. This can be adjusted to be very nearly equal to the torque of the suspension and is adjustable by a field strength adjustment. The result of this compensation is to have, very nearly, a free drifting coil which will follow the motions of a search coil in a magnetic field. This results in a rotation of a mirror proportional to the movements of the exter-

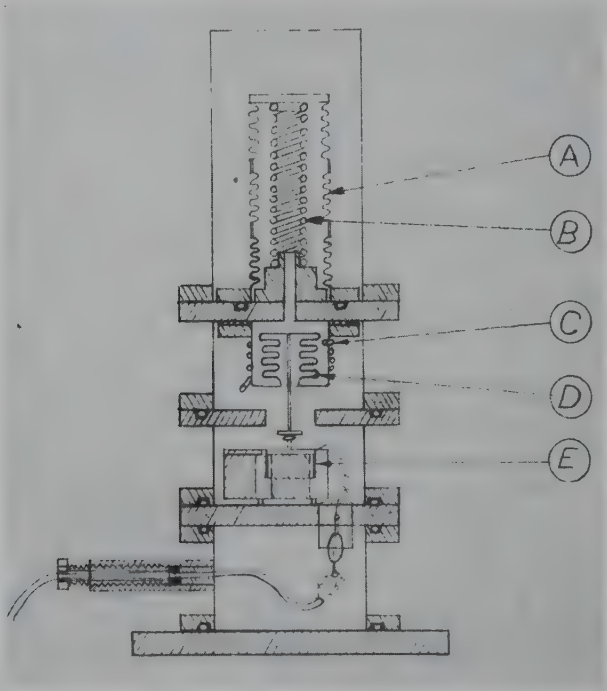


FIGURE 1.

nal bellows of the underwater unit. In the commercial fluxmeter recorder,[2] a photoelectric follow-up system allows recording of ink on paper. The fluxmeter galvanometer has been incorporated in a recorder built at Woods Hole and is illustrated later. It was possible to install a Bourdon tube in the recorder so that simultaneous pressure changes and electrical indications of the pressure changes could be recorded. These are illustrated by FIGURE 2. The pattern at the top is produced by machine and illustrates a changing wave period from approximately $2\frac{1}{2}$ seconds up to 10 seconds.

The center and bottom patterns show how the electrical recording method follows the pressure changes. It can be seen that, in a few places, where essentially a static pressure has developed, the electrical recording tends

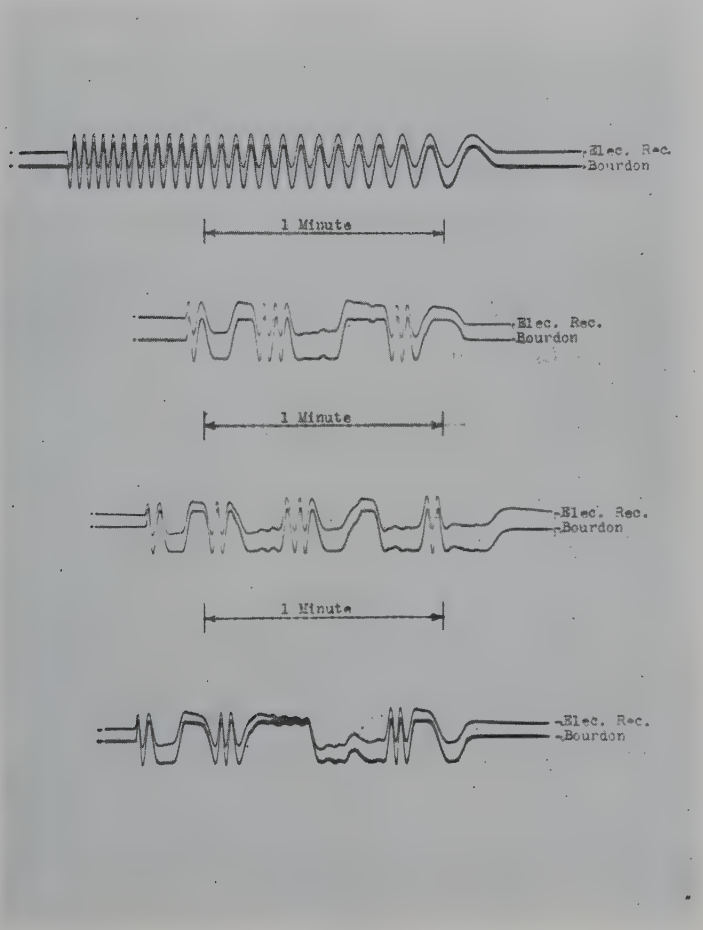


FIGURE 2.

to center. This is due to the fact that the fluxmeter galvanometer has the compensation device set to center slowly in the event that some disturbance has thrown it off scale. In addition, the slow leak has an effect here. The response to waves of various periods show it to be reduced to 90

per cent of its value, with a wave period of 44 seconds, compared to 100 per cent at 4 seconds.

The recorder, underwater unit, and power supply are illustrated in FIGURE 3. This is the recorder that produced the simultaneous records of FIGURE 2. The recorder weighs approximately 25 pounds and the under,

FIGURE 3.

water unit with ring weighs approximately 35 pounds. The power supply is an ordinary 6-volt storage battery. Approximately 1,000 feet of light rubber cable is illustrated. This equipment is convenient for measuring waves in protected areas and harbors. It can be set up in the space of an hour or two. An installation of this equipment is shown in FIGURE 4.

This is a large wooden box which has been fastened in place on the beach by stakes driven into the ground. In this particular case, the underwater unit was one mile off shore in approximately 85 feet of water. All the recording equipment is in this box and, after final adjustments are made, the box is closed and left to operate continuously or to take a 20 minute record every 3 or 4 hours. A set of records from this installation is shown in FIGURE 5. Each strip represents approximately 10 minutes of recording. This is a bottom pressure representation of surface waves and it can be seen that much manual work is required for extracting data.

It became of interest to find hidden components in ocean waves and we started the development of an ocean wave analyzer. British developments[3]

FIGURE 4

had preceded us in the field, thus the construction of an ocean wave analyzer was not original with us. As a first step in this direction, we developed a recorder to provide a record for mechanical analysis. The most simple record that would be useful in many ways was a half white, half black, record. The pressure pattern appears similar to a profile of the sea surface. The optical system of this recorder is shown in FIGURE 6. This is a plan view of the recording system. Lamp A is a line filament lamp with its filament in a horizontal position. Light from this lamp is collected by lens B and an image of the filament is produced at knife edge C. At this point a small portion of the light is cut off so that a cold filament end would not be reproduced on the photographic paper. This light is reflected by mirror D and is collected by lens E. After being reflected by fluxmeter mirror F and

mirror G, the image is focused on the recording paper. The portion of the image that corresponds to the cut off point at knife edge C is intended to fall near the center of the paper. This results in a bright line of light which has an abrupt halt in illumination. As the recording paper moves in an upward

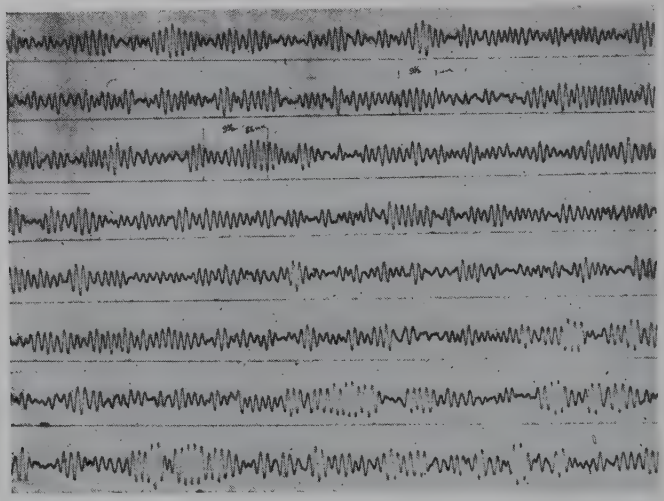


FIGURE 5.

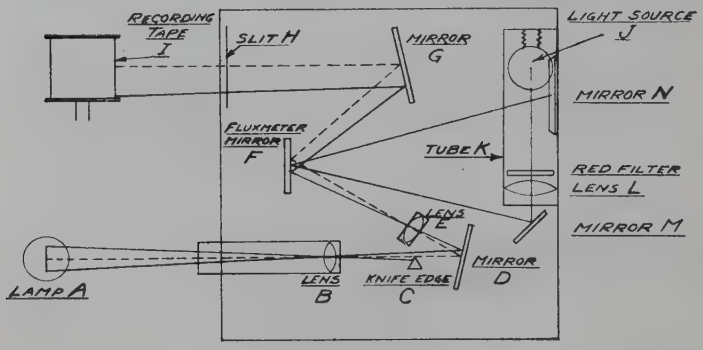


FIGURE 6.

direction, fluxmeter mirror F is rotated by the pressure fluctuations and the line of light moves across the face of the paper. As a result, half the photographic paper is exposed and a profile pattern is produced. Components J, K, L, M, and N are introduced to provide a visual filament image at a viewing slit, so that fluctuations can be observed.

We have added a control box, so that the program-switching clock and controls are contained in a unit separate from the recorder. The recorder is usually mounted by fastening a brass plate to the floor with long bushings and lag screws. The recorder has three legs with adjustments and this is placed over the brass plate. Locknuts are provided on each side of the brass plate so that positive and rigid leveling is obtained.

A few records from this instrument are shown in FIGURE 7. These were obtained off Cuttyhunk, Massachusetts. The width of the tape is 35 mm. and the timing marks are at 30 second intervals. The record is first received as a 200 foot roll of exposed tape. It is photographically processed and dried.

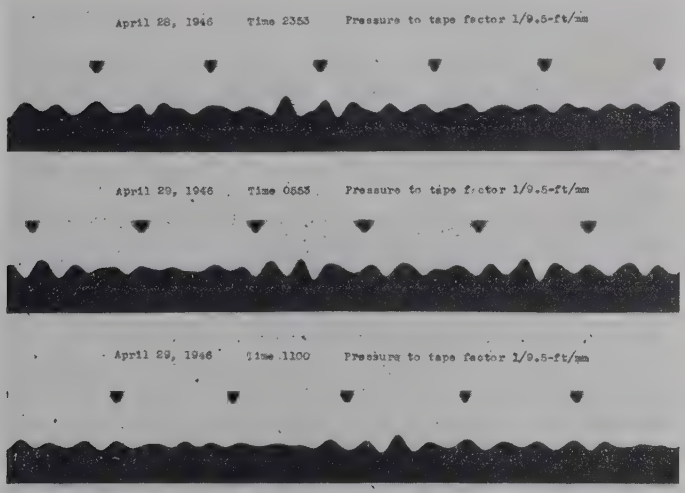

April 28, 1946 Time 2353 Pressure to tape factor 1/9.5-ft/mm
April 29, 1946 Time 0553 Pressure to tape factor 1/9.5-ft/mm
April 29, 1946 Time 1100 Pressure to tape factor 1/9.5-ft/mm

FIGURE 7.

The analyzer for these tapes is shown in diagrammatical form in FIGURE 8. Operation is as follows: A 5 foot, 4 inch strip of record is placed around the circumference of a 20-inch drum, B. This is approximately 19 minutes of recording. Close to the circumference of the drum, shown by the block marked "photoelectric scanner," is a source of illumination, a lamp and a photoelectric cell. A portion of the record is illuminated and an image of the illuminated section is produced at a point in the box. At the point of the image, a set of slits is provided and unwanted portions of the record can be blocked out. The portion of the image desired passes through the open slide and falls on a photocell. As the drum is rotated, the photoelectric scanner sees the wave record as a bundle of frequencies. The signal from this portion of the circuit is sent through a fixed frequency filter. The frequency is approximately 125 cycles. The signal resulting from this filter is amplified

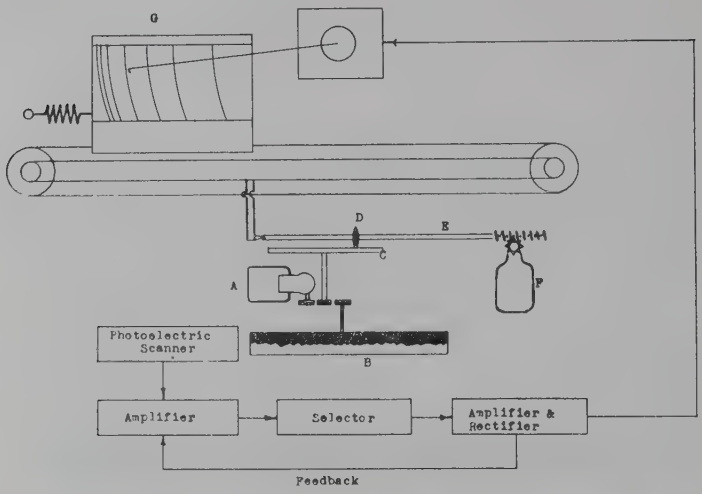


FIGURE 8. Ocean Wave Analyzer. Mechanical Diagram.

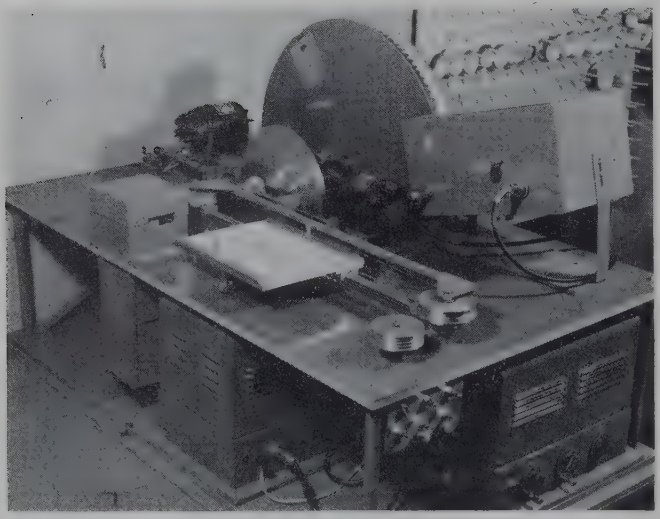
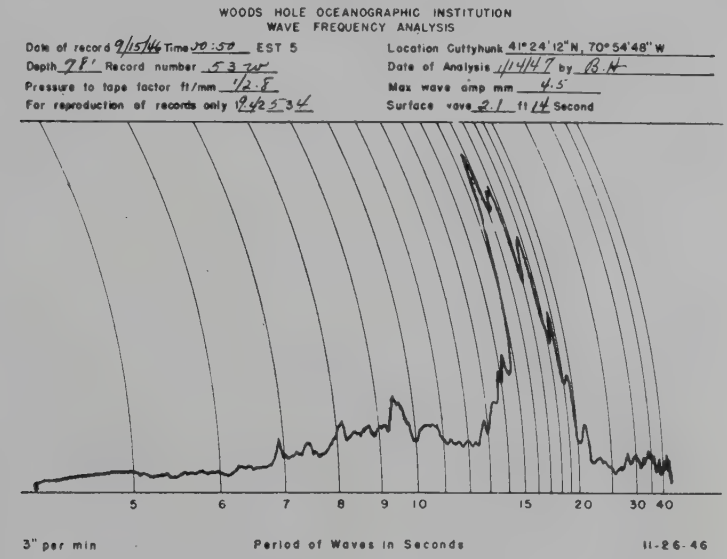


FIGURE 9.

further and a portion of the signal is sent back to the last stage of the first amplifier so that better selection is obtained.

The final output of the amplifier is rectified to operate the pen arm of the


WOODS HOLE OCEANOGRAPHIC INSTITUTION
WAVE FREQUENCY ANALYSIS
Date of record 9/15/46 Time 10:50 EST 5
Location Cuttyhunk 41°24'12"N, 70°54'48"W
Depth 78' Record number 53 7W
Date of Analysis 1/14/47 by B.H
Pressure to tape factor ft/mm 12.8
Max wave amp mm 4.5
For reproduction of records only 12 42 53 34
Surface wave 2.1 ft 14 Second
5 6 7 8 9 10 15 20 30 40
3" per min
Period of Waves in Seconds
11-26-46

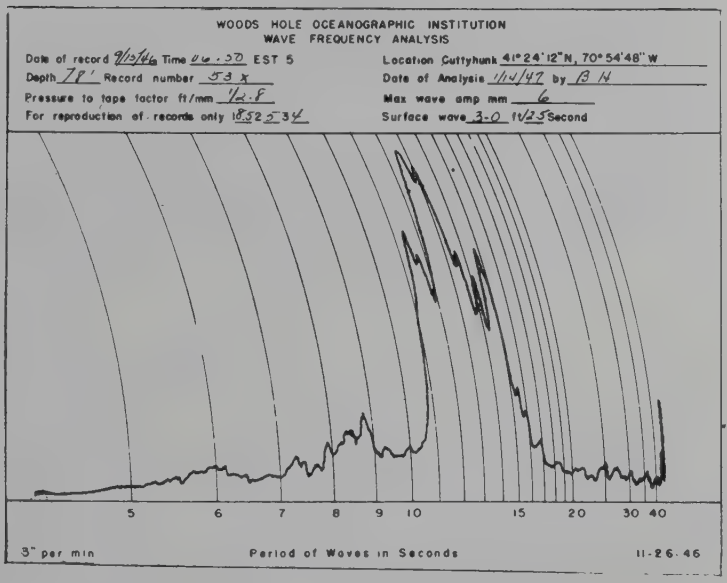

WOODS HOLE OCEANOGRAPHIC INSTITUTION
WAVE FREQUENCY ANALYSIS
Date of record 9/15/46 Time 06:30 EST 5
Location Cuttyhunk 41°24'12"N, 70°54'48"W
Depth 78' Record number 53 X
Date of Analysis 1/14/47 by B H
Pressure to tape factor ft/mm 12.8
Max wave amp mm 6
For reproduction of records only 18 52 53 34
Surface wave 3-0 ft 25 Second
5 6 7 8 9 10 15 20 30 40
3" per min
Period of Waves in Seconds
11-26-46

FIGURE 10.

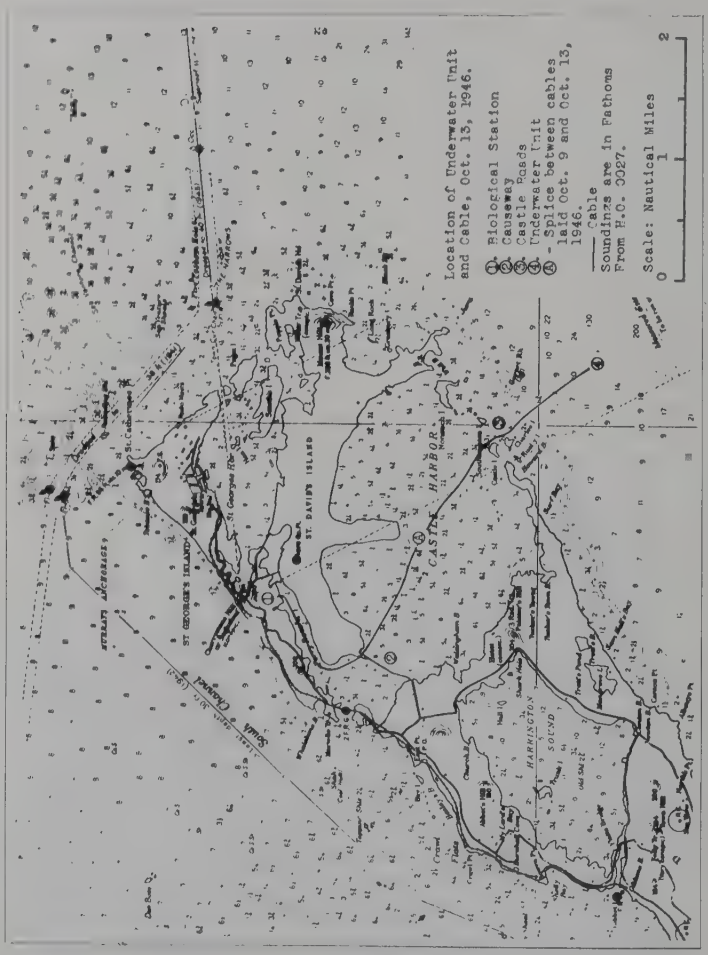

Location of Underwater Unit and Cable, Oct. 13, 1946.
Biological Station
Causeway
Castle Roads
Underwater Unit
- Splice between cables laid Oct. 9 and Oct. 13, 1946.
Cable
Soundings are in Fathoms From H.O. 3027.
Scale: Nautical Miles
0
1
2
ST GEORGE'S ISLAND
ST DAVID'S ISLAND
CASTLE HARBOR
HARRINGTON SOUND
Quaker Channel

FIGURE 11.

instrument. The rest of the device is to move the chart table to a position corresponding to various speeds of the drum. The wave spectrum is obtained by speeding up the drum and allowing it to decelerate slowly.

The chart table is moved in the following sequence of operations. Disc C, with motor A which is a brass disc, approximately 9 inches in diameter, rotates at the same speed as drum B. On the face of this disc, a small leather roller D rolls by friction contact. This is attached to shaft E, which is free to rotate, and the bearings are made so that it can move along its length. However, it is constrained in this lengthwise motion by a worm cut on the end of the shaft, which engages a worm gear attached to motor F. This is a synchronous motor. The action of the worm on the worm gear

FIGURE 12.

is such as to cause the shaft to progress to the left, as disc C rolls roller D. However, the action of the motor F is to move the shaft to the right. The constants are adjusted so that shaft E must rotate at 120 r.p.m. to remain at a fixed position. At low speeds, roller D is near to the circumference of disc C and at high speeds D is near the center of disc C. The end motion of shaft E is connected through a system of cables to the chart table B. The chart used is calibrated for particular recording tape speeds. A picture of the analyzer is shown in FIGURE 9. The drum B is shown in the background with a wave record around its circumference.

FIGURE 10 shows analyses of waves during a near hurricane, September, 1946, which passed off Nantucket, Massachusetts.

We intended to install some of our equipment at Bermuda and, in the fall of 1946, two of our field personnel went to St. Georges, Bermuda, and in months following, they installed an underwater unit southeast of Castle Harbor. The area concerned is shown in FIGURE 11. The underwater unit was first placed in approximately 130 feet of water and the cable was placed in Castle Harbor and Ferry Reach to allow recording at the Bermuda Biological Station. The length of the cable was approximately 5 miles. The underwater unit was identical to one shown in FIGURE 1. It was mounted to the top of a 450-pound concrete block with steel straps forming an apex over the unit. The block was approximately 2 feet square and 1 foot thick. Much difficulty was found in retrieving this anchor unit as it was found to be too heavy for this type of work. A later arrangement is shown in FIGURE 12. It consists of a frustrum of a cone, built of light steel rod covered with wire screen. In addition, several cable coils were placed so that the unit could be retrieved and a light cord fastening each coil of cable would be broken. In this way, the unit could be brought to the surface without actually raising any of the original cable.

References

1. RICH, T. A. 1940. *Memorandum on Fluxmeter Theory.* General Electric Company.
2. General Electric Company. Cat. No. 32C120.
3. BARBER, N. F., F. URSELL, J. DARBYSHIRE, AND M. J. TUCKER. 1946. A frequency analyser used in the study of ocean waves. Nature (London) **158:** 329–332.

Contribution No. 444

ORIGIN AND DEPOSITION OF DEEP SEA SEDIMENTS

Fred B. Phleger, Jr.

(Contribution No. 444 of the Woods Hole Oceanographic Institution)

The upper layers of the Earth's crust are represented in the sea by the sediments which are being deposited from a variety of sources and at a rate which varies from place to place and from time to time. A relatively complete series of sediments should be found in deep-sea deposits if we assume that the present ocean basins have remained approximately as they are now throughout a major part of geologic time. In this discussion the term, deep-sea sediments, is used in a very broad sense but generally to include those deposits which occur on the floors of the large ocean basins below about 2000 fathoms water depth.

The absolute rate of deposition of deep-sea sediment can at present be approached accurately only by radioactive methods such as those used by PIGGOT and URRY [1942]. It should be pointed out, however, that the rates of deposition are variable even in the deep sea and that the same factors affect the rate of deposition in this environment as affect deposition on land: Variations in supply of material, variations in transporting agency, and general geographic position. An additional factor is the marine organic production of the plankton, and this is of measurable importance. Little is known of the origin of the inorganic constituents of marine sediments, but they

certainly include what may be called particles of cosmic origin, volcanic ash or dust, non-volcanic terrestrial dust, ice rafted debris, chemical precipitates, and some material which is certainly water transported. The remains of planktonic, and to a very minor extent nektonic and benthonic, organisms are of especial importance in the study of these deposits. It is almost entirely through these organic remains that the past marine environments existing when the sediments were accumulated can be reconstructed, and also the correlation of the deposits from place to place can be accomplished.

It is of interest to review some recent progress in study of deep-sea sediments and some suggestive results which have been obtained. The sequence of marine sediments can be studied by obtaining a cross-section of them in a submarine core, and the optimum condition would be to obtain cores through the sediments to bedrock. It is not possible to obtain such cores at the present state of our experience and with the funds and facilities available. It is generally agreed that a submarine coring tube which operates on the principle of a free fall into the bottom is practical to use and is very successful in terms of results. Such coring tubes are those described by HVORSLEV and STETSON [1946] and by SHEPARD and EMERY [1941]. These obtain a cross-section of the sediments up to a reported five meters in length, with an average length of perhaps 2 1/2 to three meters.

Börje Kullenberg of the Oceanographic Institute of Göteborg has constructed a new type of coring tube which he calls the piston core sampler. This simple gear collects cores up to 20 m in length and makes all other submarine coring tubes in use more or less obsolete in terms of the results obtained. The Kullenberg sampler now is being extensively used to sample deep-sea sediments on the round-the-world cruise of the Swedish Deep Sea Expedition. The writer was a guest of this expedition last summer on their trip through the Carribean and observed the Kullenberg sampler in operation. The core sampler is weighted by several hundred pounds of lead and plunges into the bottom by the momentum gained through the free fall of one meter. This is sufficient to force the tube as much as 20 m into the bottom. There is a piston inside the tube which remains stationary at the surface as the tube falls around it; the apparent effect is to eliminate most of the friction inside the tube and the inside container is completely filled to the depth of penetration. I have seen some of these cores opened immediately after being taken and they represent an excellent cross-section of the material.

This gear opens new possibilities for the study of deep sea sediments and the sequence of events recorded in them. Absolute rates of deposition will have to be determined by radioactive methods. But at least it is possible to establish a long series of events and relative rates of deposition can be fitted into what little is known of the chronology of the Pleistocene. The Foraminifera from one core taken by the Swedish Deep Sea Expedition from the Carribean Sea have been studied by the writer. This core is 1540 cm long and came from a depth of water of about 4800 m. Seventy-five short samples were taken for Foraminifera with the positions of the samples being determined by the layering in the core.

Interpretation of the approximate sequence of surface water-temperature conditions has been based upon the vertical sequence of planktonic Foraminifera faunas in the core. There are at least 12 marked shifts from tropical to very warm temperate water on the one hand to cool temperate to sub-Arctic surface temperatures on the other hand. We do not yet know enough about the ecology of these forms to estimate more specific surface-temperature conditions from the faunas. It is interesting to speculate upon the possible sequence of events represented by the faunas in this core. There is a thick layer of tropical and subtropical faunas between about 800 and 1000 cm. It seems quite possible that this may represent the second interglacial stage of the Pleistocene which we know was as warm or warmer than the present in some places and which is thought to have been at least 200,000 years in duration. If we assume that the rate of sedimentation was approximately uniform throughout the core, then this warm water fauna represents a longer period of time than any other.

If this represents the second interglacial, then the sub-tropical and cool-temperate faunas lying above it must represent the third glacial, the third interglacial, and the fourth glacial. On this interpretation, temperature shifts beneath about 1000 cm may also represent glacials and an interglacial and it is possible that the core may have penetrated most of the Pleistocene.

The pioneer work of Piggot and Urry has shown that the absolute rate of deposition in the deep sea is variable. But if we may generalize on rates of deposition in this environment, we may say that a rate of from one centimeter in 500 years to one centimeter in 1000 years is a fair generalization on the basis of our present knowledge. This core deposited at this rate would take between 750,000 and 1,500,000 years, and this length of time is of the same order as previous estimates for the length of Pleistocene based upon equally deficient data.

The conclusions based upon the circumstantial evidence from this core are very suggestive. The variations in the Foraminifera faunas are very real and represent marked fluctuations in the climate of the sea water in which they lived. Long cores from the sea basins such as this offer the possibility of establishing and correlating a series of marine events of the more recent past from an undisturbed record. If these events can be tied into a carefully placed series of cores on which absolute dates can be fixed by radioactive methods, then we shall know a great deal about the rates of deep-sea sedimentation. Also, we can establish a Pleistocene chronology which should be more complete than any chronology based upon the deposits found on land.

References

HVORSLEV, M. S., and STETSON, H. C., Free-fall coring tube; a new type of gravity-bottom sampler, Geol. Soc. Amer. Bull., v. 57, pp. 935-950, 1946.

PIGGOT, C. S., and URRY, W. D., Radioactivity of ocean sediments, IV; the radium content of the sediments of the Cayman Trough, Amer. J. Sci., v. 240, pp. 1-12, 1942.

SHEPARD, F. P., and EMERY, K. O., Submarine topography off the California coast; canyons and tectonic interpretation, Geol. Soc. Amer. Spec. Paper 31, pp. 55-56, 1941.

Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts

(Manuscript received June 22, 1948; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 23, 1948 as part of the Alfred C. Lane Memorial Symposium on the Earth's Crust; open for formal discussion until September 1, 1949.)

Contribution No. 446

PRELIMINARY STUDIES ON THE VIABILITY AND DISPERSAL OF COLIFORM BACTERIA IN THE SEA*

By BOSTWICK H. KETCHUM, CORNELIA L. CAREY, AND MARGARET BRIGGS
WOODS HOLE OCEANOGRAPHIC INSTITUTION, WOODS HOLE, MASS.

THE DISPOSAL of sewage in the sea is widespread and increasing. There is, however, little information to indicate how much sewage a given body of water will accommodate and even less on the fate of the pollution bacteria in the sea. The economic effects of polluted estuaries are already evident, since large areas have been closed for the taking of shellfish and many beaches throughout the country have been posted as unsatisfactory. These problems will probably become more acute, because the disposal of sewage is essential and the sea provides an efficient means of dispersion.

Harbors and estuaries frequently contain many thousands of bacteria per ml, a large proportion of which may be enteric species. In the open sea, however, the bacterial counts normally range from 50-200 per ml, and the coliform bacteria are never found in open, unpolluted sea water. This tremendous decrease in numbers occurs within a short distance from the mouth of the harbor or estuary (Calif. State Dept. Pub. Health 1943; Knowlton 1929; Mass. Dept. Pub. Health 1936; Warren and Rawn 1938; Weston 1938; Winslow and Moxon 1928). It is clear, therefore, that the introduced bacteria do not persist for extended periods in the sea. The relative importance of dilution of the polluted water by sea water, of the death of the coliform bacteria, of sedimentation and predation by animals has never been clearly assessed in the marine environment.

Our studies on this problem have included laboratory investigations of the viability of *Escherichia coli* in sea water and surveys of some polluted areas selected in the hope that the various factors in the disappearance of pollution bacteria could be evaluated. The results described here must be considered of a preliminary nature.

The results of our laboratory investigations of the death rate of *Escherichia coli* in sea water will be described first. Previous investigations of this problem have given widely divergent results, varying from death rates much more rapid than are found in fresh waters (Calif. State Dept. Pub. Health 1943; Carpenter, Setter and Weinberg 1938; ZoBell 1936, 1946) to the conclusion that sea water is neither antiseptic nor inimical to enteric bacteria (Dienert and Guillerd 1940). We have found that the laboratory treatment of the sea water influences the results greatly. The use of artificial, synthetic or diluted sea water cannot be expected to give results which will correspond to the natural phenomenon.

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* Contribution No. 446 from the Woods Hole Oceanographic Institution.

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When natural, unpolluted sea water is brought into the laboratory and stored in the dark a tremendous growth of the bacterial population takes place. This growth and the effect of adding *E. coli* to the water are shown in Figure 1.* The total population of the raw sea water increases to a maximum in three days, then decreases to a more or less uniform population of about a million cells per ml. A slight initial increase in bacterial numbers is also detected in the water to which the coliforms were added. This period of growth of the mixed population is followed by a decrease in numbers so that the final populations are approximately the same whether *E. coli* were added or not.

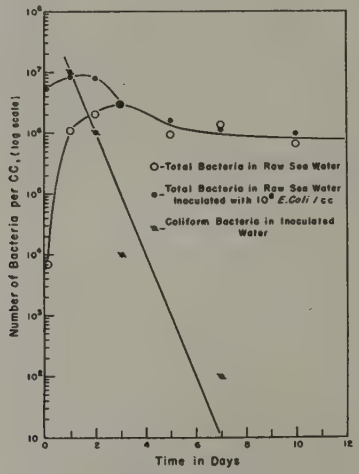
Number of Bacteria per CC. (log scale)
Time in Days
O-Total Bacteria in Raw Sea Water
Total Bacteria in Raw Sea Water Inoculated with 10⁸ E.Coli / cc
Coliform Bacteria in Inoculated Water

FIG. 1. Growth of marine bacteria and the viability of *Escherichia coli* in untreated sea water.

The concentrations of *E. coli* were estimated independently in this experiment by inoculating lactose broth fermentation tubes. The indicated numbers of *E. coli* thus obtained are also shown in Figure 1. They decrease regularly from the initial inoculum of 10^8 cells/ml and after approximately seven days only a millionth of this population persists. Clearly, the conditions which are suitable for the growth of marine bacteria are inimical to the growth or persistence of the coliforms. It appears that the final populations in both the raw sea water and in the water inoculated with *E. coli* consist of the normal sea water organisms.

If, instead of using untreated sea water, *Escherichia coli* are intro-

* The numbers were determined by plate counts after 7 days' growth on a medium containing 1 gm glucose, 1 gm peptone, 0.05 gm NaH_2PO_4, 15 gm agar in 1 liter of aged sea water.

duced into water sterilized by autoclaving or by boiling, the results shown in Figure 2 are obtained. In the autoclaved water the death rate of the coliform bacteria is very slow. The maximum decrease observed was to one-fifth of the total population in a period of seven days. In the boiled water the death rate is more rapid and is similar to the rate found in the untreated sea water. It is clear from these results that the bactericidal action of sea water is destroyed by the heat of autoclaving, but is unaffected by the milder boiling treatment.

Another observation shown in this figure is that a second or subsequent inoculum of *E. coli* dies off more rapidly than the first. In these experi-

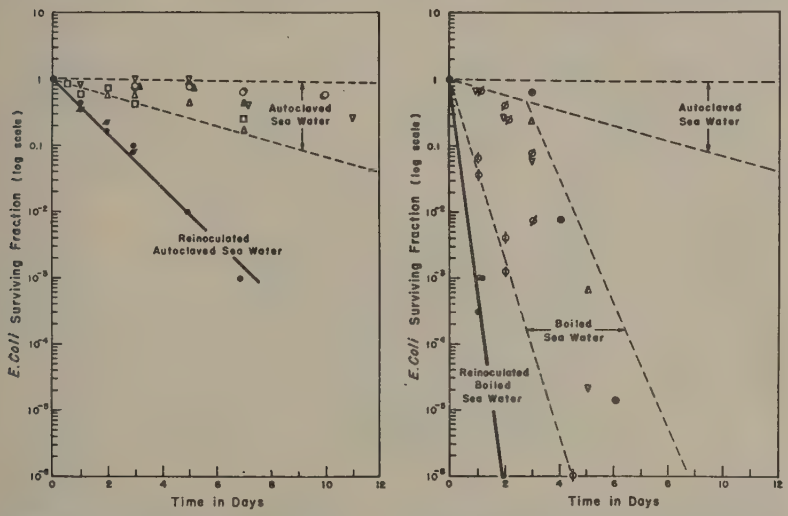

FIG. 2. The viability of *Escherichia coli* in autoclaved and in boiled sea water. The original inoculation of E. coli provided a population between $5x10^7$ and $5x10^8$ cells/ml. The surviving fraction is plotted. Different symbols represent different experiments.

ments the water receiving the first inoculum was stored until no viable cells were found. This took about 20 days for the autoclaved sea water, 5 to 10 days for the boiled water. When another inoculum of *E. coli* was added to the water, the bacterial counts decreased as shown by the heavy lines. The death rate in the reinoculated autoclaved water is eight times as great as the rate observed for the first inoculum. A threefold increase in rate was observed with the boiled water. It may be presumed that the greater death rates observed with reinoculated water correspond to what would be obtained in polluted estuaries.

The coefficients of death rate, as shown in Table I, summarize the results of these laboratory investigations. This coefficient is the reciprocal of the time (in days) for the population to decrease to one-tenth its original

TABLE I

AVERAGE COEFFICIENTS OF DEATH RATE OF ESCHERICHIA COLI IN SEA WATER TREATED IN VARIOUS WAYS

Treatment	Coefficient of Death Rate (k)	
	First inoculum $days^{-1}$	Subsequent inocula $days^{-1}$
None	1.00	
Boiled 5 min.	1.15	3.48
Autoclaved 10-15 min.	0.04	0.35

value. Thus, a coefficient of 1.0 means that a tenth of the population dies daily; the coefficient 0.04 indicates that 20 days are required for an equivalent mortality. These experiments show that sea water has a potent bactericidal action. The activity is decreased greatly by autoclaving, but not by boiling the sea water. It is increased by previous "pollution" of the water with *E. coli.*

Further investigations are necessary to determine how the bactericidal activity of sea water varies with natural conditions. Is there a seasonal variation which might be correlated with variations of the normal population of the sea? Is the bactericidal activity greater in polluted harbors than in the open sea, and what are the effects of dissolved organic matter, oxygen supply and other variables associated with pollution? What is the identity or nature of the bactericidal activity?

Some of our experiments suggest that antibiotic substances produced by marine organisms may be responsible for the death of the pollution bacteria. They do not exclude, however, the possibilities that bacteriophage or autolytic or degenerative products of the coliforms themselves may also be involved. It is possible that all three contribute to the final action. It is significant, however, that Rosenfeld and ZoBell (1947) have recently described the production of antibiotic substances by several species of marine bacteria. None of these antibiotics was inimical to gram negative species and *E. coli* was not included among their test organisms. In our experiments pour plates of the normal sea water bacteria were made and the population allowed to develop for 48 hours. The surface of one of each pair of plates was then flooded by a suspension of *E. coli,* the excess being poured off. After a total time of four days the plates were inspected and clear areas were found surrounding some of the sea water bacteria. These results suggest that some of the sea water forms produce substances inimical to *E. coli.*

It is pertinent to inquire whether the results of these laboratory experiments bear any relation to the phenomena which occur in nature. In the sea the mortality of the bacteria may be completely obscured by the circulation and mixing of water masses. The dilution of the polluted water

with sea water disperses the bacteria, and this effect must be accounted for in order to observe the death rate. In complicated estuarine situations, where there are several sources of contamination, it becomes especially difficult to differentiate between mortality and dilution. The recent development of an instrument for the continuous recording of salinity and temperature, however, has made it possible to conduct more rapid and accurate surveys of hydrographic conditions. From the data thus obtained the rate of dilution of the introduced contaminated water can be estimated. It is this possibility which has stimulated our interest in the field.

A comparatively simple picture of the fate of sewage bacteria in sea water may be found at the Sewer Outfall at New Bedford, Massachusetts. Here the sewage is introduced from a seven-foot diameter outfall pipe at a depth of 30 feet, 1100 yards offshore into water that is relatively uncontaminated. During the rising tide the flow of sewage is decreased and sometimes stops completely. During the falling tide the sewage wells

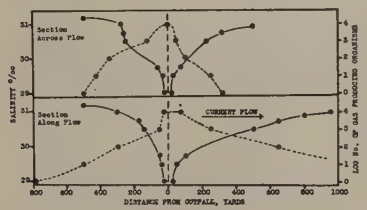

Fig. 3. The salinity and the indicated numbers of organisms producing gas from lactose broth at various distances from the New Bedford Sewer outfall.

out of the pipe in sufficient volume so that it is readily detectable. It is, indeed, difficult to obtain samples directly in the upwelling column since the boat's course is deflected by the rising and spreading current. A tidal current flow of about half a knot sweeps past the location of the outfall, and, on the ebb, carries the polluted water seaward. Several series of observations on the distribution of salinity and coliform bacteria have been made at this location.

The surface distribution of salinity and bacteria along the axis and across the axis of the tidal current are both shown in Figure 3. As would be expected, the salinity of the outfall water is low compared to the surrounding sea water of Buzzards Bay. The introduced sewage is diluted with 13-14 volumes of sea water by the time it appears at the surface. In crossing the axis of current in the neighborhood of the outfall, the bacterial numbers increase to a maximum at a location near the outfall and then decrease again on the other side. The distribution of salinity and of bacteria along the axis are similar except that the downstream distances required to reach a given concentration are greater.

The bacterial numbers are, however, always lower than would be predicted on the basis of dilution alone. To illustrate this point the dilution, expressed as percent outfall water in the sample,* and the surviving percentage of bacteria in the sections across and along the axis of current flow are plotted in Figure 4. If the bacterial count decreased only because of the dilution of the water the two sets of data would be superimposable. The surviving percentage of bacteria, however, is always less than the percent dilution of the water.

The extent by which the numbers of bacteria are less than the expected numbers is shown in Figure 5, where the numbers of bacteria found are

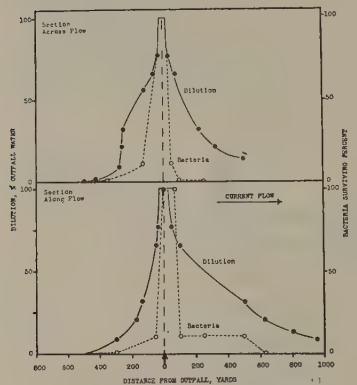

FIG. 4. The dilution of the outfall water, as calculated from the salinity change, and the percentage of bacteria surviving at various distances from the New Bedford Sewer outfall.

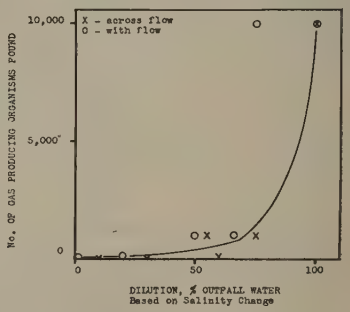

FIG. 5. The number of gas-producing organisms found plotted against the dilution of outfall water as calculated from the salinity change.

plotted against the dilution of the water. If the bacteria diminished in direct proportion to the dilution of the water a straight-line correlation would be expected since dilution of the water by 50% would lead one to expect half of the original bacterial population. The bacterial numbers are, however, substantially lower than can be accounted for by dilution alone. In the simplified situation at the New Bedford Sewer outfall, therefore, it is clear that the coliform population disappears much more rapidly than would be expected on the basis of simple dilution by sea water.

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* Each sample of water is considered a mixture of the polluted, fresher water with sea water, i.e.

$$XS_o + (1-X)S = S_1$$

in which X is the fraction of polluted water of salinity S_o, and S and S_1 are the salinities of the sea water and of the diluted water sample.

A more complicated picture is found in polluted estuaries where the circulation of the water masses play a more important role. The water exchange in an estuary includes a net outward movement of surface water contributed by rivers at the head of the bay and a net inward movement of the denser more saline sea water at mid-depth or near the bottom. Along the length of the estuary vertical mixing tends to increase the salinity and the volume of the outflowing surface waters with the result that the total surface outflow at the mouth of the estuary is greater than the flow into the estuary from the rivers. An imporant corollary of this generalization is that introduced pollution can be removed only in the surface waters, since any material which sinks to the deeper water moves in a net "upstream" direction.

It may be pointed out that the float tests, which have long been standard techniques in the study of such situations, give only a small part

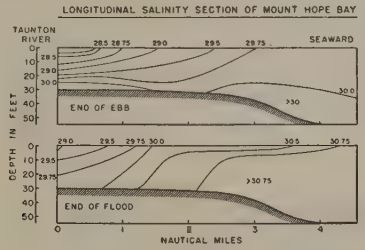

Fig. 6. The distribution of salinity in a longitudinal section of Mount Hope Bay at the end of the ebb and flood tides.

of this complicated picture. The floats show only the net flow of the surface waters, and give no information concerning the rate of vertical mixing. In studying the effects of various wind conditions the use of floats is especially deceptive. The wind drives the float more rapidly than it drives the water. The same wind, furthermore, increases vertical turbulence to such an extent that the pollution is dissipated more rapidly instead of being carried farther as suggested by the float results. Measurements of the salinity of the water provide the most useful tool in studying the exchanges and dilution of various water masses.

Typical salinity contours in Mount Hope Bay, below Fall River, Massachusetts, at the end of the ebb and flood tides are given in Figure 6. These data, collected by the continuous salinity-temperature recorder, illustrate the general principles of estuarine circulation described in the Survey of the River Tees (1931, 1935, 1936). The picture at low tide shows relatively flat, elongated salinity contours demonstrating the greater surface flow of the less saline and consequently lighter river water. The deep water retains much of its dense, high salinity character. Follow-

ing the flood tide all of the contours are shifted upstream, and the gradients of salinity distribution with depth are more gradual.

An important contribution of water circulation to the disposal of pollution is the rate of dilution of the contaminated water. This occurs,

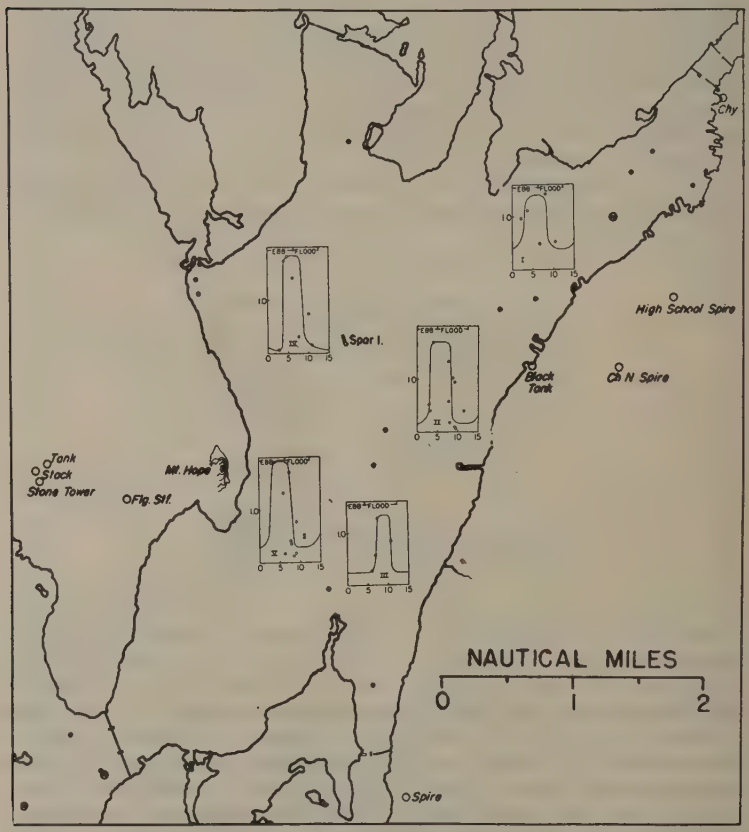

FIG. 7. The ratio between the observed and the expected bacterial counts at various locations in Mount Hope Bay at different stages of the tide. The expected numbers are computed by correcting the numbers introduced in the Taunton River (N.E. corner of chart) by the degree of dilution with sea water.

not only by horizontal mixing, but also by the vertical mixing of the surface water with the more saline deeper water. The rate of this mixing is increased as the density gradient between the surface and deeper waters decreases. As shown by the salinity contours in Figure 6 vertical mixing

will be most rapid at the end of the flood tide, since at this time the vertical distribution of salinity and density is most uniform. Any increase in wind force will increase the rate of this mixing, which will tend to diminish the salinity gradients still further.

The distribution of bacteria in relation to the phase of the tide in Mount Hope Bay is shown in Figure 7. In this figure the bacteria are represented by a ratio between the number actually found and the number expected. The number expected is calculated by correcting the number introduced in the river water at the head of the bay by the degree to which this water has been diluted by mixing with sea water. The ratio thus obtained is plotted against the time after high water at each of the locations shown in this figure. If dilution were the only factor operative in this area all of these curves would be flat and show no variation with the tide. The fact that all of them increase above unity indicates that there are contributions of bacteria from sources other than the river mouth. This is to be expected since the area is densely populated and several sewerage systems empty directly into the bay. The interesting fact, however, is that in spite of this additional pollution, the numbers at each location fall far below the expected numbers during the period of high tide. Since the effect of dilution has been cancelled out it is clear that this diminution is the result of other processes which deplete the bacterial population.

To summarize, our investigations have indicated that the coliform bacteria disappear rapidly from normal sea water under laboratory conditions. This disappearance is not related in a simple way to the chemical content of sea water since autoclaving the water eliminates its bactericidal activity. The lethal factors, or substances, are apparently organic in nature and heat labile.

That the bactericidal property of sea water is important under natural conditions is indicated by the fact that the disappearance of coliform bacteria in the sea is much more rapid than can be accounted for by the dilution of contaminated water with sea water. It is fortunate indeed that this is the case, else our heavily polluted harbors would be unbearable.

Several additional problems must be studied in order to complete the picture. It would, of course, be desirable to determine the nature of the bactericidal substance or factor in sea water. The distribution of bactericidal activity in waters and muds collected from polluted areas and at varying distances from shore should aid in identifying its character. The potency of a given body of water may be expected to have an important relation to its ability to accommodate introduced pollution. Finally, considerably more fundamental information is needed concerning the principles which govern the mixing of water masses. When this information is available it should be possible to plan marine outfalls so that the introduction of pollution will lead to the minimum interference with the fisheries and economy of the area.

Acknowledgments

The authors gratefully express appreciation for the interest and advice of Dr. Selman A. Waksman, who initiated our laboratory studies, and of Dr. Alfred C. Redfield, who has encouraged our investigations of sewer outfalls and estuarine conditions. The contributions of Dr. William L. Ford, who conducted the hydrographic investigations and collected the salinity data used in this report, and of Mr. C. M. Weiss, who made the bacterial counts at New Bedford, are gratefully acknowledged.

References Cited

Calif. State Dept. Pub. Health. 1943. Report on a pollution survey of Santa Monica Bay beaches in 1942. 69 pp. Calif. State Printing Office, Sacramento, Cal.

Carpenter, L. V., Setter, L. R. and Weinberg, M. 1938. Chloramine treatment of sea water. *Amer. Jour. Pub. Health,* 28: 929-934.

Dienert, F. and Guillerd, A. 1940. Etude de la pollution de l'eau de mer par le déversement des eaux d'egouts. *Ann. d'Hyg. Pub.,* Ser. 5, 18: 209-217.

Knowlton, W. T. 1929. *B. coli* surveys, Los Angeles ocean outfalls. *Calif. Sewage Works Jour.,* 2: 150-152.

Mass. Dept. Pub. Health. 1936. Report of the special commission on the investigation of the discharge of sewage into Boston Harbor and its tributaries. House No. 1600. Wright & Potter Printing Co., Legislative printers, Boston, Mass.

Rosenfeld, W. D. and ZoBell, C. E. 1947. Antibiotic production by marine microorganisms. *Jour. Bact.,* 54: 393-398.

Survey of the River Tees.

Part I. Hydrographical. 1931. [*Gt. Brit.*] *Dept. Sci. and Indus. Res., Water Pollut. Res. Tech. Paper* 2: 92 pp. H. M. Stationery Office, London.

Part II. Alexander, W. B., Southgate, B. A. and Bassindale, R. 1935. The Estuary, Chemical and Biological. *Water Pollut. Res. Tech. Paper* 5: 171 pp.

See also summary in *Mar. Biol. Assoc. Jour.* U.K.N.S., 20: 717-724, 1936.

Warren, A. K. and Rawn, A. M. 1938. Disposal of sewage into Pacific Ocean. *Modern Sewage Disp.* pp. 202-208. Federation of Sewage Works Assoc., New York.

Weston, A. D. 1938. "Disposal of Sewage into the Atlantic Ocean," *Modern Sewage Disp.,* pp. 209-218. Federation of Sewage Works Assoc., New York.

Winslow, C. E. A. and Moxon, D. 1928. Bacterial pollution of bathing beach waters in New Haven Harbor. *Amer. Jour. Hyg.,* 8: 299-310.

ZoBell, C. E. 1936. Bactericidal action of sea water. *Soc. Expt. Biol. and Med. Proc.,* 34: 113-116.

————. 1946. *In* Marine Microbiology. Chapter XVI, 182-192. Chronica Botanica Co., Waltham, Mass.

Contribution No. 448

A CAMERA FOR PRODUCING ONE-DIMENSIONAL REDUCTION IN NARROW RECORDS[1]

By

HILARY B. MOORE

Woods Hole Oceanographic Institution

Many instruments yield long, narrow records which are of an awkward shape for reproduction. In the course of work under Navy contract NObs-2083, numerous fathograms were obtained which showed the diurnal movements of the "deep scattering layer." This layer is believed to be of planktonic origin (J. B. Hersey and H. B. Moore, 1948).[2] The part of the fathogram which includes the scattering layer is about two inches deep, while a day's record is three feet long. The instrument described here combines photographic reproduction, which is preferable in this case, with the desired change in the ratios of the vertical and horizontal scales. Similar records appear likely to be of use to geologists in studying long stretches of the ocean bottom.

The paper record is wound by a toothed drum under a lucite sheet which fills the field of a 5 x 4-inch film in a camera (Fig. 1). There is a light-tight case from the camera lens to the lucite sheet, the part of this next to the lens being fixed, the rest being mounted on a vertically-sliding carriage. Close to the lucite, the case narrows to an adjustable horizontal slit one millimeter in diameter. Two 100-watt lamps are mounted on the carriage in housings which concentrate the light on the part of the fathogram opposite the slit. The carriage slides on vertical guides, and is slowly lowered by a suspending string. This string is unwound from a smaller drum fixed on the same axle on which the record-driving drum rotates. The ratios of the diameters of these drums is so chosen that, as the slit descends and scans the length of the lucite sheet, a little over three feet of fathogram is drawn past it.

Fig. 2A shows a normal photograph of a day's fathogram, reduced to reproducible size. Fig. 2B shows the same length of this record as reproduced by the slit camera, but with only the upper part containing the scattering layer included. Not only are the details of the diurnal migration of the layer much clearer in the latter, but also the distortion produced by the slope and curvature of the vertical coordinates is much reduced. Details of lettering on the original are,

[1] Contribution No. 448 from Woods Hole Oceanographic Institution.

[2] Progress report on scattering layer observations in the Atlantic Ocean, Trans. Amer. geophys. Un., *29* (3): 341–354, 1948.

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of course, lost in the contraction, but a label fixed to the lucite sheet may be included in the negative if desired.

While no new principle is involved in the apparatus, it is proving so useful that a description appears justified. It could readily be modified to take other types of records, or to produce any desired degree of contraction.

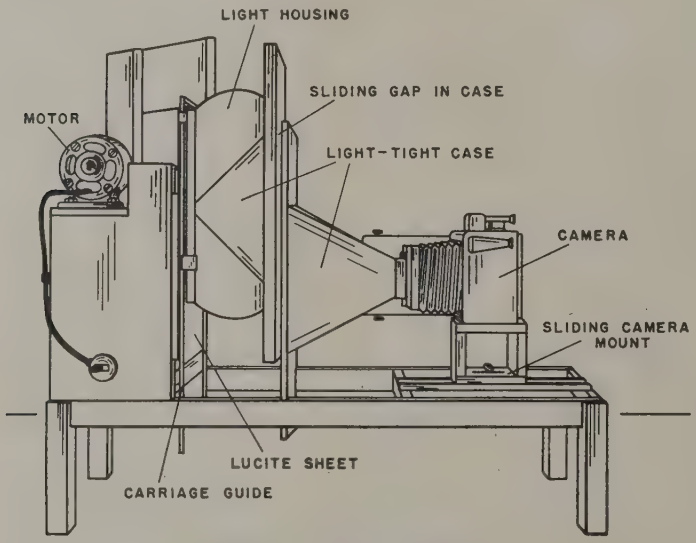

Figure 1. Elevation of camera.

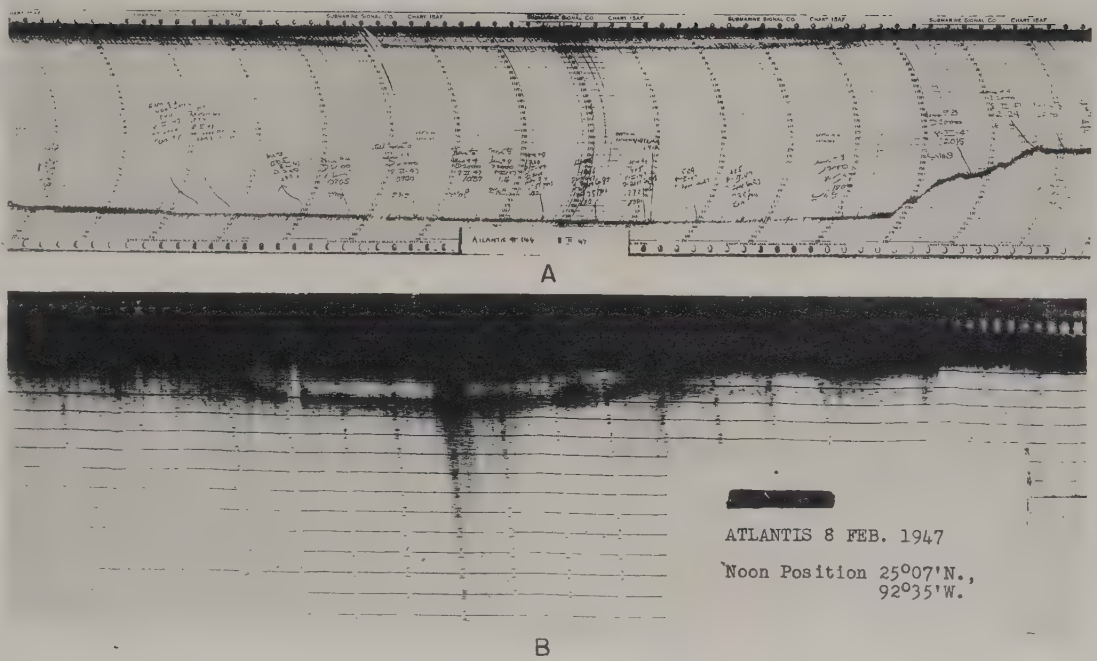

Figure 2A. Fathometer trace with normal dimensions, X 1/5. 2B. Upper part of above fathometer trace reproduced with slit camera.

Contribution No. 450

SEISMIC REFLECTIONS FROM BENEATH THE OCEAN FLOOR

J. B. Hersey and Maurice Ewing

(Contribution No. 450 of the Woods Hole Oceanographic Institution)

Abstract--Apparatus and procedures are described with which seismic reflections have been obtained from the ocean bottom and from deeper horizons. The area surveyed lies between Bermuda, the Greater Antilles, and the United States. All records obtained in an east-west strip, 70 to 80 mi wide, extending from 61° W longitude south of Bermuda to 71° W longitude and thence southward as a strip 200 to 300 mi wide to about 23° N latitude, show a single prominent reflecting horizon at depths exceeding 500 ft below the bottom (assuming the seismic velocity in the bottom sediment to be equal to or greater than that of sea water). In this area the bathymetric data indicate that the bottom is either flat or relatively smooth. The records from other parts of the area are, with few exceptions, more complicated, correlating with bathymetric evidence of a rougher bottom there. A system is outlined for classifying reflection records obtained in deep water with suggested geologic significance of the various record types.

Introduction--During the period from September 1946 through June 1947, reflection observations have been made by the Woods Hole Oceanographic Institution's R/V Atlantis at 133 locations over 530,000 sq mi of the western Atlantic basin in the area bounded by lines from New York to Bermuda to Puerto Rico, by the Greater Antilles, the Bahamas, and the Eastern Coast of the United States. This report describes the instrumentation and procedures used and presents evidence that reflections were recorded from reflecting horizons below the ocean floor. Reflection records of different types were obtained depending on location. The correlation of these record types with submarine topography is discussed.

Instrumentation--The source of seismic energy was a pound of TNT exploded in the water at depths of the order of 100 to 300 ft in the earlier part of the work and depths of two or three ft in the later work. The detector was a Rochelle salt crystal hydrophone which fed an audio amplifier through a step attenuator and a Western Electric Type RA363 octave band pass filter. The amplifier has a flat response over the frequency range from 100 to 5000 cps. Oscillographic recordings were made by photographing a Dumont Type 208 oscilloscope with a 16 mm Bolex movie camera with its shutter and arresting mechanism removed to make it a strip camera. The film speed was approximately six inches per second. Timing marks were put on the film early in the work by a chronometer-controlled signal impressed directly on the input to the oscilloscope. Later the same timing signal was used to light a small neon bulb placed beside the oscilloscope tube.

Shooting procedure--All observations were made with the Atlantis hove to and the hydrophone lowered to depths varying from 150 to 1000 ft. The shallower depths were preferred throughout most of the work since the records were less complicated. Before a shot was fired the attenuator was set to avoid overloading on the direct shock wave. Shortly after the shot but before the first bottom reflection the attenuator was re-set manually for proper sensitivity to record the first bottom reflection. After it had been observed the attenuator might be re-set again for the second bottom reflection, and so on until no further reflected energy was observed. The time between reflections, about five to ten sec, was quite sufficient to make this adjustment, and usually the correct attenuator settings could be predicted from records of the previous location, even though the distance between stations was usually 60 mi.

At each location several shots were recorded using various settings of the octave filter. Since it is common experience in seismic prospecting for oil that very low sonic frequencies, 30 to 50 cps, are most useful in reflection work, low frequency records were attempted. In the early part of the work no useful records were obtained below the 150 to 300 cps band, so this and bands of higher frequency were used almost exclusively. Toward the end of the program an amplifier sharply tuned at 75 cycles gave good records in several areas.

The geometry of set-up as used through the early cruises led to an unnecessarily complicated record, but since considerable data were taken with this set-up, it is described. Since the shot

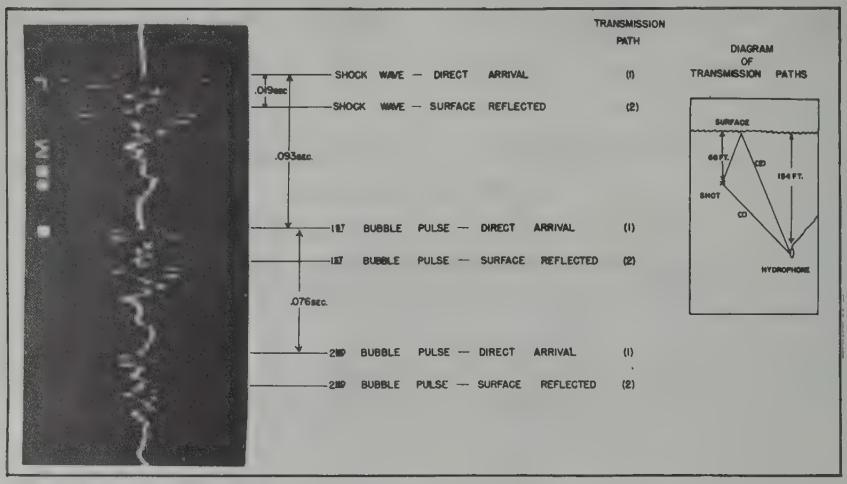

Fig. 1--Sound from a deep shot recorded at short range

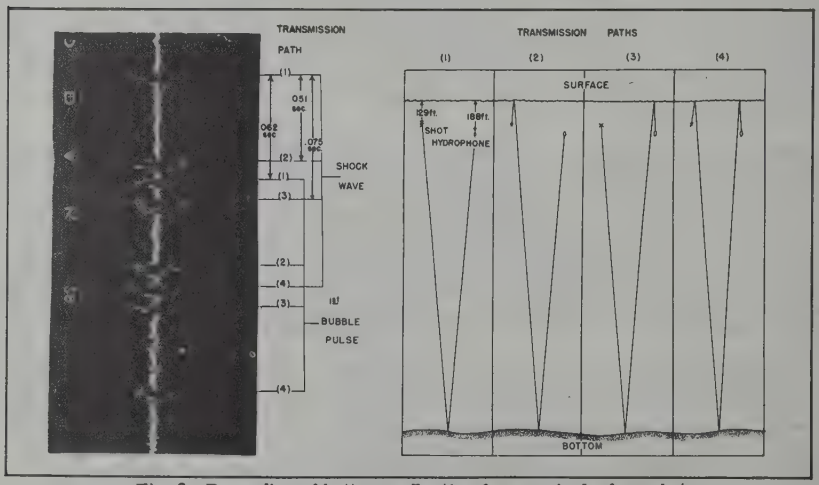

Fig. 2--Recording of bottom reflection from a single deep shot

was located 100 to 300 ft below the surface, two shock waves normally went to the bottom; the direct shock, and its surface reflection. In addition to these, the first and second oscillations of the gas bubble of the explosion also sent out pulses. Since each was effectively double because of surface reflection a total of six readily resolvable energy pulses were reflected at the bottom. If the bottom has acted as a plane specular reflector and there has been no distortion of the pulses through the water, each pulse is detected in turn as it passes the hydrophone; each is also detected again after reflection at the surface. Thus if all pulses have sufficient intensity as many as 12 separate pulses may be recorded to represent the reflected energy from a single explosion after one bottom reflection. In practice it was found that generally either four or eight separate pulses were recorded These can be identified as coming from the direct shock, or the direct shock and the first oscillation of the gas bubble. Figure 1 shows a record of the direct and surface reflected pulses of a shot fired at a depth of 66 ft. Figure 2 shows an unusually clear record of a single bottom reflection.

In this case eight pulses are recorded. The reflection from a rough or inhomogeneous bottom would easily make this already complicated series of pulses hopelessly complicated and there would be little hope of interpreting the results in any detail.

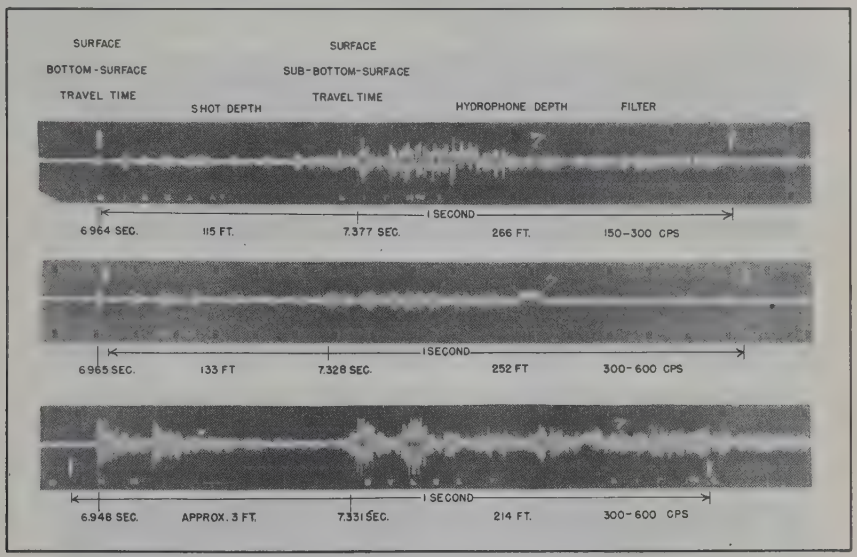

Fig. 3--Comparison of bottom reflections from deep and shallow shots

The apparatus and shooting procedure described are admittedly cumbersome and inadequate for studying bottom reflections. The fact that good recognizable reflections were obtained in certain localities must arise from the extreme simplicity of the structure of the bottom there and from the excellence of the water as an acoustical medium. In the course of the work some improvements were made both in instrumentation and shooting techniques which have improved the quality of the results, notably shooting at very shallow depths (less than three ft) so as to allow the explosion to blow out without oscillations of the gas bubble. This technique simplifies the signal due to a single reflection from a possible 12 pulses to two at most. Figure 3 presents a comparison of the two techniques showing the first bottom reflection for several shots at Station 4499 where both techniques were employed. Other developments such as (1) investigation of the frequency range below 100 cps, (2) use of multichannel recording, multiple detectors, and automatic volume control, and (3) a method of taking observations underway are being made as rapidly as possible, and can be expected to improve future results.

Bottom reflection data--If the ocean bottom were perfectly flat and homogeneous, a single sharp echo would be received from it. Where it is stratified, secondary reflections may be received due to reflection at surfaces beneath the bottom. Where it has topographic relief, secondary echoes may be obtained by side reflections from the topography. The principal criterion for deciding whether a given echo came from a side reflection from the bottom topography or from a reflection beneath the bottom was the frequency composition of the reflected sound. It was expected that passage through rock or sediment would attenuate the high frequencies more than the lows, as happens in seismic work on land.

The following is a summary of the evidence of reflection beneath the ocean bottom found in this study.

(1) Secondary reflections were observed in all cases.

(2) They were readily separable on the basis of frequency into those recorded at all frequencies, which are taken to be side reflections from bottom topography, and those recorded only at low frequencies, which are taken to come from below the bottom.

(3) Side echoes are prevalent in regions where the recording fathometer shows topographic relief.

(4) The most clear-cut sub-bottom echoes are found in the region which shows least topographic relief.

(5) At all stations over a large area, a single sub-bottom reflection was observed. The time lag of this reflection behind the bottom reflection varied in a continuous manner over the region, as would be expected if it represented reflection from an extensive sub-bottom surface.

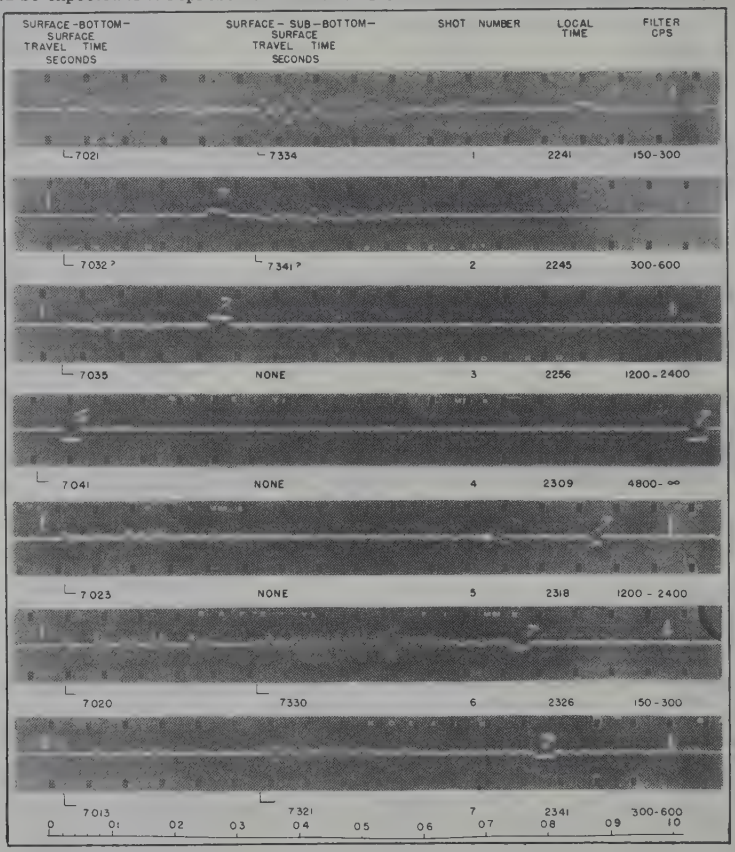

Fig. 4--Records of the first bottom reflections for all shots at Station 4498; type M records

To illustrate the principles of analysis, Figure 4 presents records in various frequency bands at Station 4498. At all frequencies there is a reflection at about 7.013 to 7.041 sec which corresponds to the ocean bottom. In the lower frequency records there is a later reflection at 7.321 to 7.341 sec which comes from a reflecting surface below the bottom. Two lines of evidence prove that the later reflection occurs at a continuous and more or less horizontal surface beneath the ocean bottom. (1) Over a large area these two reflections are obtained, and the time interval between them varies in a gradual manner. (2) The absence of high frequency sound in the later reflection is best explained by differential absorption within the bottom rocks.

The Swedish physicist, WEIBULL [1947], has reported similar bottom reflection studies in which secondary reflections were recorded. These were interpreted as coming from reflecting horizons below the bottom. His paper does not exhibit oscillograms of bottom reflections nor does it state how the secondary reflections are known to have penetrated the bottom sediments. Hence, it is difficult to compare the two investigations. However, from conversations with Weibull it is known that he did not make any frequency analysis of the reflected energy but demonstrated penetration by recording shots fired at radically different depths at the same location. The fact that

secondary reflections were recorded which showed the same time lag after the bottom reflections regardless of shot depth was taken as proof that they were reflected from an horizon below the ocean floor.

Record types--Records shown in Figure 4 form one of the principal types into which the records so far observed can be classified. In these the sub-bottom structure is extremely simple. The bottom reflection has an abrupt beginning and it is brief. The interval between the bottom and sub-bottom reflections is relatively quiet, and from the relative amplitudes of the bottom and sub-bottom reflections it is inferred that the acoustical contrast between the materials at the sub-bottom reflecting horizon is at least as great as that between the water and the bottom. The hypothesis is advanced that here remarkably homogeneous sediments overlie hard rock. Records of this general character are designated type M.

Two variations of type M have been observed. In both the bottom reflection begins sharply and is followed by a period of relative quiet before a simple sub-bottom echo. In one the amplitude

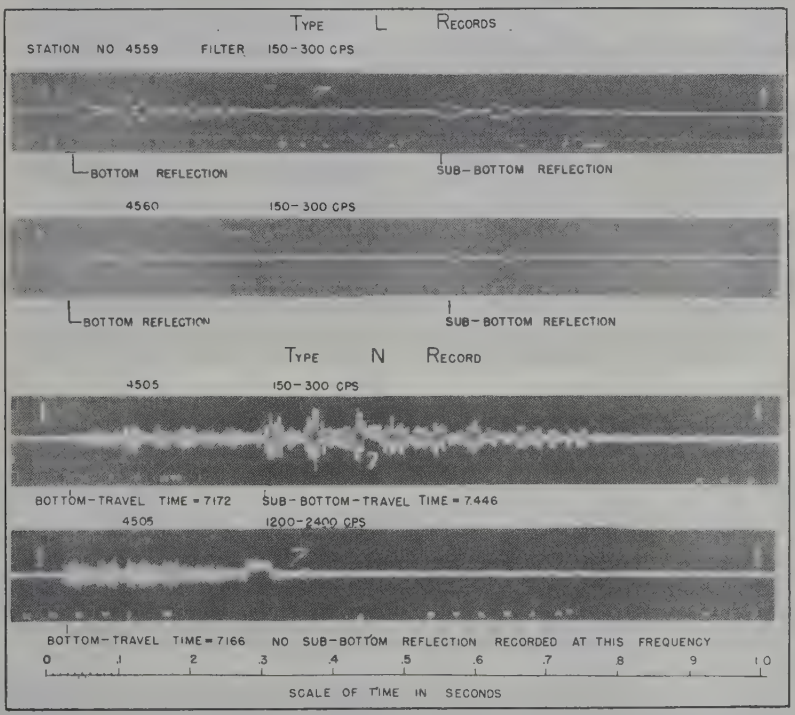
TYPE L RECORDS
STATION NO 4559 FILTER 150-300 CPS
BOTTOM REFLECTION
SUB-BOTTOM REFLECTION
4560 150-300 CPS
BOTTOM REFLECTION
SUB-BOTTOM REFLECTION
TYPE N RECORD
4505 150-300 CPS
BOTTOM-TRAVEL TIME = 7.172
SUB-BOTTOM-TRAVEL TIME = 7.446
4505 1200-2400 CPS
BOTTOM-TRAVEL TIME = 7.166 NO SUB-BOTTOM REFLECTION RECORDED AT THIS FREQUENCY
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0
SCALE OF TIME IN SECONDS

Fig. 5--Type L and N records

of the bottom echo is less than half the sub-bottom echo, while in the other it is greater by at least a factor of two. These are designated, respectively, types L and N. Examples are shown in Figure 5. Examples of L, taken at Stations 4559 and 4560 were taken from shallow shots which, because they lack bubble pulses are readily interpreted. The example of N at Station 4505, taken from a deep shot, has all the complication of the bubble pulses and in addition it is probably further complicated by side reflections from bottom topography. For this reason a high frequency record at the same station is shown. Its complicated character compared with the high frequency records shown in Figure 4, for example, indicates topographic effects are present. However, there is no trace of the set of arrivals interpreted as sub-bottom reflections on the low frequency record. This is especially striking, since as a type N record the sub-bottom reflection has about twice the amplitude of the bottom reflection.

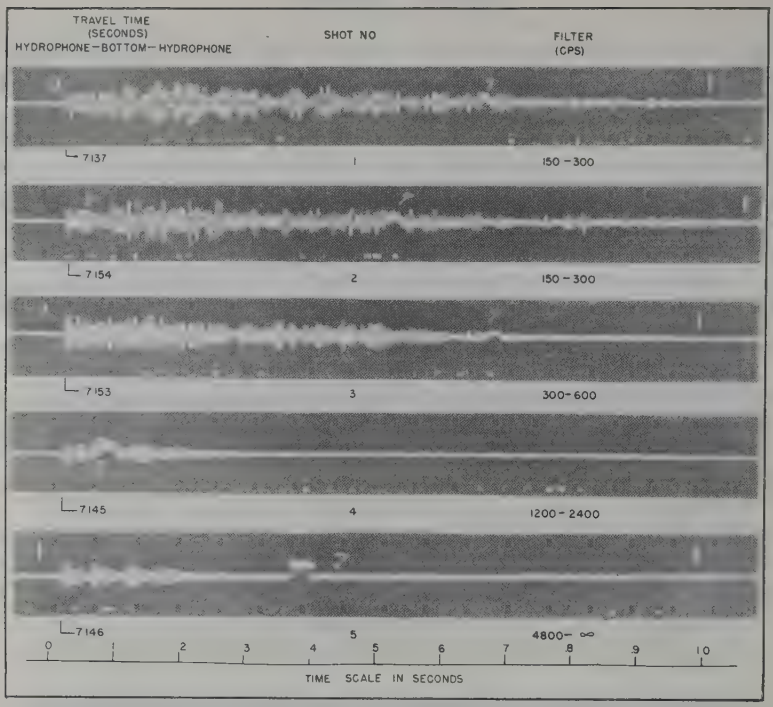

Fig. 6--Recordings of the first bottom reflection at Station 4504; type R records

At other locations such as Station 4504, shown in Figure 6, the lower frequency records show a complicated structure that does not repeat precisely from one shot to the next, but does appear to be somewhat more prolonged than the high frequency records. Here it is supposed that the sub-bottom structure is considerably more complicated. Records of this character are designated type R.

In some places, such as Stations 4483 and 4486, shown in Figure 7, the bottom reflection starts with a low amplitude forerunner followed shortly by a rather complicated group of high amplitude arrivals. This feature is recorded at low and high frequencies alike. It is frequently not reproducible and can be demonstrated to arise from reflections from elements of topography in the vicinity at some stations, though it seems possible that in some cases the correct interpretation may be a weak bottom reflection followed by a strong sub-bottom at such a shallow depth that all frequencies penetrate the bottom sediments. Where several frequencies are recorded simultaneously, it should be possible to decide between these two interpretations using differential absorption at different frequencies as a criterion for sediment penetration. Records of this character are called type F.

In still other cases such as Station 4502, shown in Figure 8, both low and high frequency records start abruptly and are very complicated. The several arrivals recorded on each are probably to be interpreted as reflections from various elements of topography in the vicinity. The method of recording used is at considerable disadvantage in that only one frequency band is recorded per shot and hence the travel-time relations are not maintained precisely for the various frequencies. Improved instrumentation on later cruises has produced records on which high and low frequency bands were recorded simultaneously. At some locations these records demonstrate that several arrivals later than the bottom reflection had not penetrated the bottom since they were clearly recorded on both high and low frequency traces. Records in which these characteristics predominate are called type T.

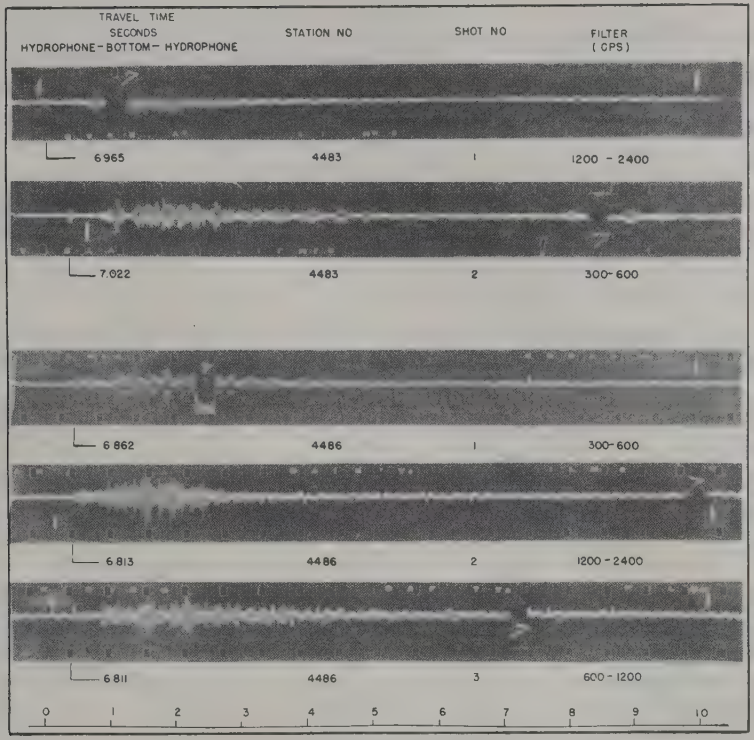

Fig. 7--Type F records

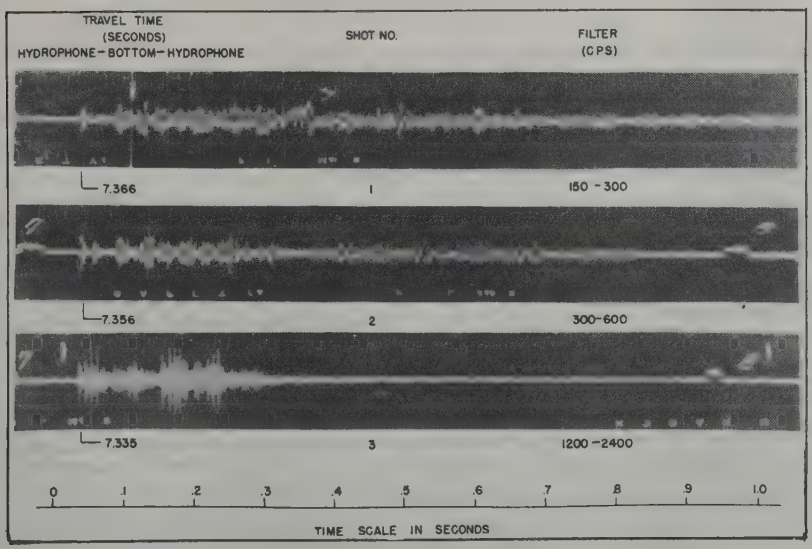

Fig. 8--Type T records

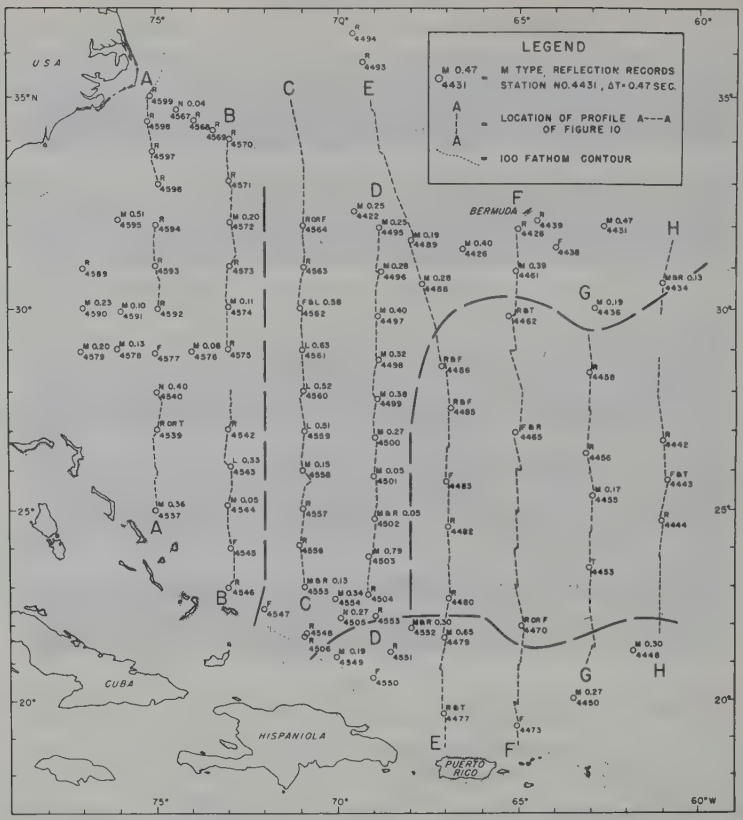

Fig. 9--Chart of station locations and reflection-record types

Correlations with bottom topography--The area surveyed is shown in Figure 9. It is about 530,000 sq mi. Stations are at intervals of about 60 mi on lines about 100 mi apart. Naturally on so open a network of stations it is impossible to correlate from station to station except for the largest structural features and in areas of gradual change.

Over much of the area a continuous fathometer record was obtained, and over the rest of it sonic soundings were made at half-hour intervals. These data permit plotting the detailed profiles of submarine topography shown in Figure 10.

The legend of Figure 10 indicates the manner of obtaining the depth from the fathometer. Data taken from the explosion records provide an independent check and are plotted on the profiles. All depths are based on 4800 ft/sec sound velocity and are about 100 fathoms too shallow as a result.

On the basis of topography alone the area is divided into four areas as shown in Figure 10. Note that Figure 10 is composed as a sort of three-dimensional chart with a latitude scale at the top and approximate longitudes indicated on the depth profiles. For accurate location of the profiles refer to the dashed lines of Figure 9. The northern and central areas are characterized by a relatively smooth bottom (profiles C, D, and the northern part of E), the eastern area by hills or ridges up to 2400 ft high (central portion of E, F, G, and H); the southern area by a gentle upslope to the ridge which forms the northern edge of the Brownson Deep (southern portion of E, F, and G); and a western area whose main topographic feature is a low ridge, seen on the two westernmost profiles on an otherwise flat bottom (A and B). The same division follows from a study of the

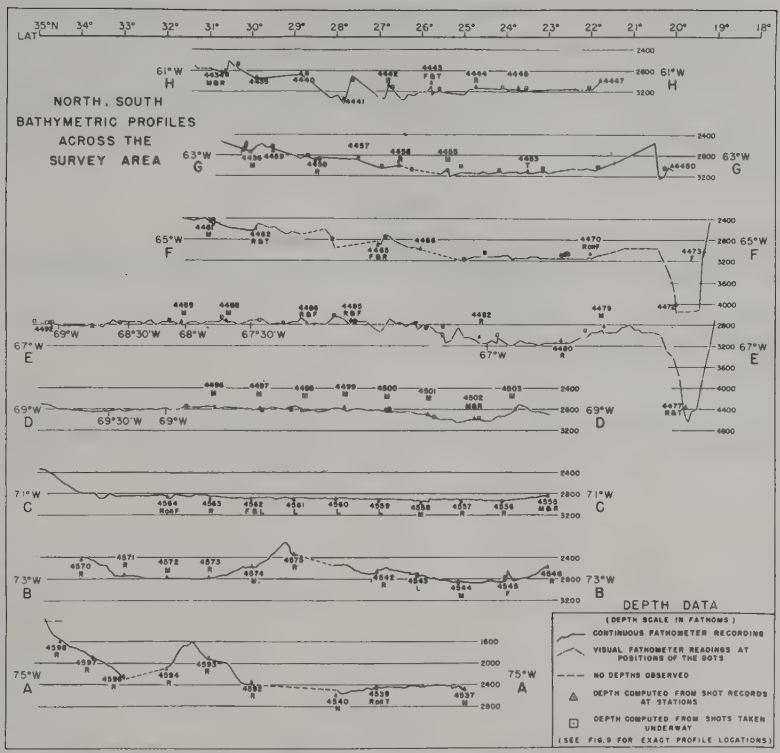
NORTH, SOUTH
BATHYMETRIC PROFILES
ACROSS THE
SURVEY AREA
DEPTH DATA
(DEPTH SCALE IN FATHOMS)
CONTINUOUS FATHOMETER RECORDING
VISUAL FATHOMETER READINGS AT POSITIONS OF THE SHOTS
NO DEPTHS OBSERVED
DEPTH COMPUTED FROM SHOT RECORDS AT STATIONS
DEPTH COMPUTED FROM SHOTS TAKEN UNDERWAY
(SEE FIG. 9 FOR EXACT PROFILE LOCATIONS)

Fig. 10--North, south bathymetric profiles across the survey area

explosion records. In the northern and central area the bottom reflections are exceptionally clear-cut, and only a single prominent sub-bottom reflection is obtained (types M, L, and N). On the basis of the widely spaced observations made to date the difference in travel time between the bottom and sub-bottom horizon appears to vary in a generally uniform manner between about 0.05 and 0.63 sec in the northern and central areas. This travel-time difference (ΔT) is given in Figure 9 and all M, L, and N stations and the areas described above are delineated by the heavy dashed lines. The majority of the M, L, and N stations have ΔT's greater than 0.2 sec, which corresponds to a layer thickness of 500 ft or more if the seismic velocity in the layer is assumed equal to or greater than that in sea water. Records from the eastern area differ markedly from those in the northern and central areas. These also differ in character among themselves but are all relatively complicated (types R, T, and F). In the southern area only a few records of useable quality have been obtained, but these indicate type M records are to be obtained on the gentle slope, while the records in the Brownson Deep are complicated in character, probably types R, F, and T. In the western area various types of records are found with M, N, and L tending to fall on the flat places and R, T, or F on the ridge or the continental slope.

Conclusions--The instrumentation and technique described have obtained records of energy from reflecting horizons below the ocean floor in deep water. A system of classification of deep sea-reflection records is presented with suggested geologic interpretation. The record types correlate in a general way with bottom topography. These conclusions are based on very widely spaced observations over the area considered, and were drawn from techniques which have since been considerably improved upon and are subject to further improvement. The inferences drawn from the data have been made conservatively and are subject to revision and amplification as more and better results are obtained. Hence this report should be considered preliminary. The work is continuing and will furnish more detailed information about this and other areas of the deep oceans.

Acknowledgments--The observations at sea were made by Stanley Bergstrom assisted by various members of the scientific party on the Atlantis. The assistance and cooperation of Captain Adrian Lane and the crew of the Atlantis in the scientific operations were important to the success of the survey and are gratefully acknowledged. (This work was carried out as an incidental part of research for the Navy Department, Bureau of Ships under Contracts NObs-39092 to Columbia University, sub-contract to the Woods Hole Oceanographic Institution and NObs-2083 to the Woods Hole Oceanographic Institution. Permission of the Navy Department to publish this material is hereby gratefully acknowledged.)

Reference

WEIBULL, WALDO, The thickness of ocean sediments measured by a reflexion method; Med. Oceanograf. Inst., Göteborg 12 (Göteborg Kungl. Vetenskaps- Och Vitterhets-Samhälles Handlingar, Sjätte Följden, Ser. B, Band 5, no. 4, pp. 1-17, 1947.

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(Manuscript received July 26, 1948; presented at the Twenty-Eighth Annual Meeting, Washington, D. C., April 28, 1947; open for formal discussion until July 1, 1949.)

Contribution No. 457

Transactions, American Geophysical Union Volume 30, Number 1 February 1949

EFFECTS OF WIND SHEAR ON SOME ASPECTS OF CONVECTION

Joanne Starr Malkus

(Contribution No. 457, from the Woods Hole Oceanographic Institution)

Abstract--A jet ascending through a fluid possessing vertical shear of the horizontal wind will show a difference in horizontal velocity from that of the ambient air. The magnitude of the difference is shown to be a function of the vertical shear and the rate of entrainment of mass into the jet.

The effect of this relative horizontal velocity on the slopes of dry thermals and on cumulus cloud processes is discussed. The observed horizontal asymmetries in the turbulence associated with trade cumulus are offered as an example.

Relative velocities between jet and surroundings

Theory--The parcel method of dealing with convection processes envisions a rising bubble of air ascending through an environment at rest. A modification, the so-called slice method [BJERKNES, 1938] takes into account the compensatory sinking of the environment. The importance of mixing between the rising air and its surroundings has required increasing attention, and recently the analogy between the hydrodynamical jet stream with its entrainment of mass from the environment and atmospheric convection has been emphasized [AUSTIN, 1948; BYERS and BRAHAM, 1948; STOMMEL, 1947]. This work has demonstrated the significant amount of mass entrainment which occurs in the rising cumulus or thermal, and entrainment has been evaluated by synoptic methods [STOMMEL, 1947]. The rate of mass entrainment is found to be of the order of one part external air to four parts cloud air every 50 mb.

Up to the present time, meteorologists have discussed a jet rising through an environment at rest. Actually, however, a variation of the horizontal wind with height is almost always observed. The question of the modification of the ascending jet by a vertical shear therefore arises.

Returning for a moment to the earlier parcel method, it is clear that a bubble ascending to a region where the wind differs from that at its origin carries its initial horizontal momentum, and therefore arrives at the upper level with an excess or deficiency of horizontal velocity, depending on the sign of the shear. Thus, if cumulus convection occurred without friction (which gives rise to mixing), it is easily seen that cumulus clouds and thermals must acquire horizontal velocities relative to the air surrounding them. Mixing, or entrainment of mass, on the way up can be seen as a factor reducing this differential velocity. Only if the mixing were infinitely great, however, could the difference be reduced to zero.

A quantitative estimate of the relative horizontal velocity between the ascending jet and its surroundings can be made very easily, under only one simplifying assumption. That assumption is based on the results of theoretical work done by TOLLMIEN [1926] and discussed by GOLDSTEIN [1938, pp. 592-600], ROSSBY [1936], and SCHMIDT [1948]. The theoretical treatment concerned the symmetrical jet which is homogeneous with its environment. For this case it was shown that the flux of mass increases linearly with distance from the nozzle. Linear increase of flux is assumed, therefore, as a beginning approximation for the atmospheric case.

Some function must also be chosen for the relation between ambient wind velocity and elevation. It turns out that this function enters the equations so simply that only a quadrature with respect to height is involved, and therefore any analytic expression which approximates the wind profile is quite satisfactory. For the purpose of simple illustration, a linear wind profile is taken here.

The problem is to find the horizontal velocity of the cloud, u_c (where the x-direction is taken to be that of the horizontal wind velocity at the level in question) as a function of elevation z. In considering a small, vertical segment of the ascending jet (see Fig. 1) between the levels z and z+dz, let M be the upward mass flux across the entire rising column at z, where the horizontal cloud

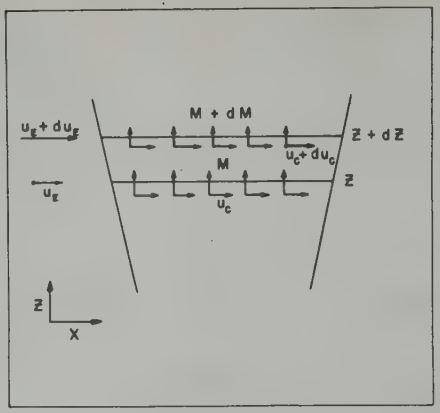

Fig. 1--Schematic vertical section of an ascending jet

velocity is u_C, and the horizontal environment wind velocity is u_E. Let the flux of outside air into the cloud between z and z + dz be dM. Since a steady state is assumed, the flux at z + dz is M + dM. Let the horizontal cloud velocity at z + dz be $u_C + du_C$ and the outside wind velocity be $u_E + du_E$.

Beginning with the law of conservation of momentum, it is clear that the horizontal momentum of the air inside the jet at the level z + dz must equal the sum of the momenta of its component masses at level z, or that

$$(M + dM)(u_C + du_C) = Mu_C + u_E dM \quad \ldots (1)$$

The exchange of momentum between jet and environment is accounted for by the term $u_E dM$ [see GOLDSTEIN, 1938; SCHMIDT, 1948; TOLLMIEN, 1926]. Multiplying out, neglecting products of differentials, and dividing through by dz, we obtain

$$u_C\, dM/dz + M\, du_C/dz = u_E\, dM/dz \quad \ldots . (2)$$

After substitution, according to the earlier assumptions, namely that

$$M = M_0 + kz \quad \ldots (3)$$

and

$$u_E = u_{0E} + hz \quad \ldots (4)$$

where the subscript 0 refers to quantities at the jet base, k is the rate of increase of mass flux with height, and h is the rate of increase of the x-component of the wind with height, and after rearrangement, the following first-order differential equation is obtained.

$$du_C/dz + u_C k/(M_0 + kz) = (ku_{0E} + khz)/(M_0 + kz) \quad \ldots (5)$$

The solution is found to be

$$u_C = c/(M_0 + kz) + (2ku_{0E}z + khz^2)/2(M_0 + kz) \quad \ldots (6)$$

where c is the arbitrary constant of integration. If at the lower boundary of the jet (where z = 0), $u_C = u_{0E}$, then

$$c = M_0 u_{0E} \quad \ldots (7)$$

and the solution can be rewritten in convenient form as

$$u_C = u_{0E} + Khz^2/2\,(1 + Kz) \quad \ldots (8)$$

where $K = k/M_0$.

Equation (8) shows that the relative horizontal velocity between cumulus cloud (or thermal) and its environment is a function of both the external wind shear and the rate of mass entrainment. A quantitative example has been plotted in Figure 2.

In this graph, the vertical shear of external wind represented by the solid curve is three m/sec in 1200 m. Since shear enters the relative velocity linearly, a simple vertical scale adjustment will give any desired linear shear. The dotted curve gives $u_C - u_{0E}$ as a function of z for a rate of entrainment such that the ascending mass flux at the top of the 1200 m layer is 2.5 times that at the bottom. This rate is slightly higher than the average rate found by STOMMEL [1947] in trade cumulus, and higher than the larger value used by AUSTIN [1948] for middle-latitude convective clouds. The dashed curve represents $u_C - u_{0E}$ when the rate of entrainment is doubled.

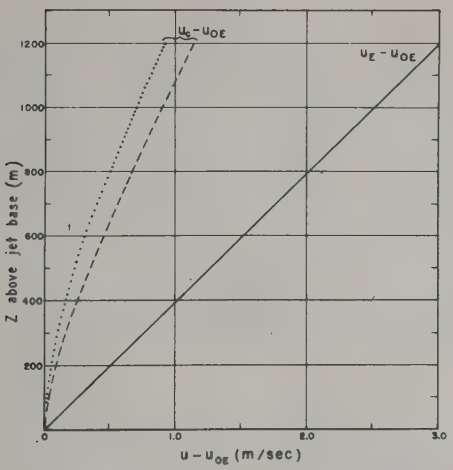

Fig. 2--Graph showing cloud velocity u_c as a function of height, compared to external wind velocity u_E; dotted curve is for rate of entrainment such that mass flux at top of cloud is 2.5 times that at base; dashed curve is for double this rate of entrainment

The relative horizontal velocity between jet and surroundings, after a 1200-m ascent, is on the order of two m/sec. Doubling the rate of mass entrainment makes a difference of only 0.3 m/sec. It is easily seen that doubling the external shear, on the other hand, doubles the relative velocity; hence shear is the more critical parameter.

Evidence--Cumulus clouds have frequently been noted to be moving with a speed different from that of their environment, but conclusive quantitative data are so far lacking. However, one case of interest was revealed by a series of lapse-time motion pictures taken at Woods Hole Oceanographic Institution on February 21, 1948. Many observers noted that the convective cumulus clouds over the water apparently were moving in the downwind direction with a speed faster than the wind, since cloud fragments were seen streaming out upwind. A subsequent examination of upper winds revealed, indeed, a strongly negative wind shear throughout the region below the estimated cloud base.

Slopes of thermals

It is but a simple step from (8) to the calculation of the actual slope of the ascending thermal chimney. To give an approximate picture of how this slope is modified by vertical wind shear and mass entrainment, a constant rate of ascent of the air v is assumed.

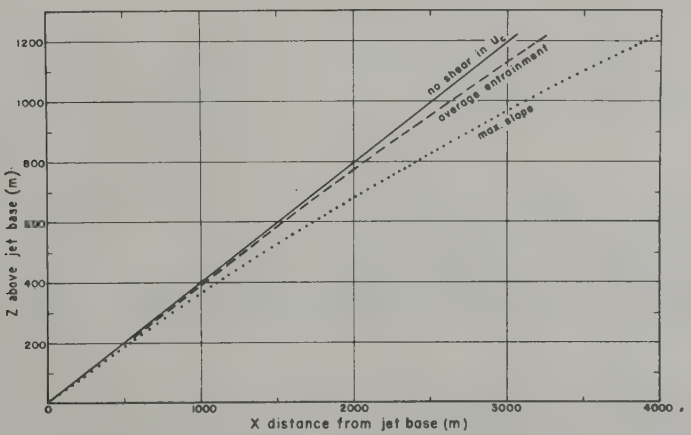

Fig. 3--Graph showing actual slope of thermal when horizontal base velocity u_{0E} is 2 1/2 times the rate of ascent

Then, under steady-state conditions, the horizontal displacement x of the thermal at level z is

$$x = \int u_c \, dz/v + \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where z/x is the slope of the thermal, and where the constant of integration can be evaluated from the boundary condition that at the base of the thermal, its x-displacement is zero.

Substituting u_c from (8), the solution is

$$x = u_{0E}\, z/v + h/2K^2v\,[(1 + kz)^2/2 - 2\,(1 + Kz) + \log_e\,(1 + Kz)] + 0.75h/K^2v \quad . \quad . \quad . \quad . \quad (10)$$

In Figure 3, the solid line represents a thermal without external shear (or without mixing with an environment with shear), when the scale is so adjusted that the horizontal velocity u_{0E} stands in a ratio of 5/2 to the rate of ascent. (According to LANGE [1945], glider pilots report that 85 per cent of thermals observed at 1000 ft altitude ascend more slowly than six ft/sec.) When the vertical distance is taken as 1200 m, and the external shear made positive and equal to that of the previous example (see Fig. 2), the dotted curve represents the maximum thermal slant (that slant corresponding to entrainment so high that the cloud mass rising from a lower level is negligible compared to that entrained). The maximum slope is approximately 5/1.5. When the increase of mass flux is reduced to a reasonable value, that of 2.5 M_0 in 1200 m as in the previous section, the slant is shown by the dashed line, the slope of which is approximately 5/1.86. It is clear from the graph that doubling the entrainment will make very little difference in the slope. In fact, at 1200 m it increases the x-distance by less than 75 m. It can therefore be concluded that for most thermals, a slope calculated from the surface wind alone is probably quite satisfactory for soaring purposes. The effects of wind shear have been shown not to be large with normal values of mass entrainment, and furthermore, on days characterized by thermals, the rate of change of wind with elevation is usually relatively slow.

Effects of the relative horizontal velocities on cumulus-cloud processes

Discussion--Horizontal translation of ascending jets of air relative to their surroundings may be expected to influence the growth and motion of cumulus clouds.

Visual observations of such clouds reveal, especially when the processes are accelerated by lapse-time motion pictures, that a cumulus is not simply an aggregate of droplets moving as a coherent body, but rather that it is a transient, dynamic balance between rapid growth and equally rapid destruction. For example, it is a common observation that when an average midsummer cumulus moves out over the cooler ocean, thus leaving its energy source, the entire cloud disappears in five to 20 min time. Lapse-time photographs further suggest that part, at least, of a cloud's motion is achieved by growth in some sections and dissipation in others.

The connection between these observations and the predicted relative horizontal jet velocity can now be made. Although a detailed analysis would still be premature, it is quite reasonable to suppose that as the ascending jet moves horizontally through the air, the entrainment of outside air becomes asymmetrical, being greatest on the windward (by windward is meant the upwind side with respect to the relative velocity $u_r = u_E - u_c$) edge, while on the leeward side, parts of the liquid cloud may actually be detrained or pulled out of the ascending jet by friction. At the present time, the evidence in favor of this hypothesis is based on qualitative observations only: First, it is common on lapse-time motion pictures to see parts of the liquid cloud streaming out on just one side, becoming caught in the downward countercurrent [SCHMIDT, 1948, pp. 13-18] just exterior to the jet and disappearing, giving rise to the typical rolling motion associated with moving cumulus. (Commonly, the streaming out is noticed on the side toward which the cloud leans with height, since winds more often increase with elevation through the cloud layer. This would imply that the cloud has a relative motion upwind through the air.) Second, clouds have often been observed to remain standing near mountaintops for considerable periods, despite fairly strong winds. The latter is probably an extreme example of air moving through a cloud. The horizontal cross-section of a cloud in which the entrainment is asymmetrical might be expected to show a corresponding asymmetry, therefore, between the region of turbulence and the observed liquid cloud, as in Figure 4.

In Figure 4, the cloud region represented by δ, which has been dragged out of the ascending jet, can be expected to be dying out, while a new cloud section is forming in region D. Thus the cloud as a whole might be said to have a component of propagation velocity due to new growth on one edge and decay on the opposite edge. Whether this component adds to or subtracts from the external wind velocity has been shown to be critically dependent upon the shear. That the turbulent region can be associated with the rising jet and a nascent or vigorous cloud is corroborated by much evidence [AUSTIN, 1948; BYERS and BRAHAM, 1948] that young, growing cumulus clouds are highly turbulent, while old or dissipating clouds are not. However, the test of this, as of any other hypothesis must lie in experimental verification, or observational examples. Such an example appears to be offered by a series of horizontal traverses through trade cumuli made by the Wyman-Woodcock expedition of April 1946 [WYMAN and COLLABORATORS, 1946].

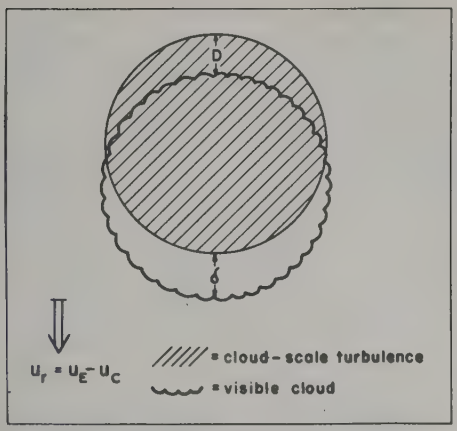

Fig. 4--Schematic illustration of expected asymmetry between liquid cloud and turbulence of ascending jet, where u_r is relative horizontal velocity in the positive x-direction between jet and ambient air; D is the region of turbulence and no cloud, while δ is the region of cloud and little or no turbulence

The observations--Trade cumulus commonly are found in patches, roughly 100,000 ft in diameter, separated by wider clear areas. Their bases are at the top of the well-mixed and almost dry-adiabatic homogeneous layer which extends ordinarily to about 2000 ft above the sea. The cloud tops usually terminate at the base of the stable layer remaining from the trade inversion, which occurs on the average at 7500 to 8000 ft, with only an occasional break-through. Part of the routine of the 1946 Caribbean expedition were airplane traverses made by a Navy patrol plane (PBY-5A) which maintained an airspeed of about 100 knots, during which an angle of attack meter and an accelerometer were recording continuously. The results of those flights in the wide areas entirely free from clouds have been discussed by LANGWELL [1948], who showed that the sum of the vertical speeds (called here vertical gust speeds) obtained by the two instruments together can be regarded as a relative measure of the small-scale turbulence present. Fortunately, several traverses were also made through regions containing scattered or broken cumuliform clouds, at altitudes ranging from 3000 to 7000 ft, but most commonly at 6000 to 6500 ft. When these data were worked up following the method described by Langwell, it was found in general that the vertical gust speeds outside the clouds averaged 0.2 m/sec while those inside the clouds averaged slightly higher than 1.7 m/sec. Exceptional regions, however, at the cloud borders occurred with regularity. With only one exception (discussed later) there was a region 600 to 1000 ft in extent just outside the visible cloud where gust speeds as great as or often greater than those inside the cloud were detected. Furthermore, corresponding regions were noted just inside the opposite border of the cloud where speeds nearly as low as the outside average were measured. These recordings of cloud-scale turbulence in the clear, and clear-scale turbulence in the cloud suggest an asymmetrical picture of trade cumulus like that shown in Figure 4. However, before these regions can be identified with the D and δ, respectively, of Figure 4, it must be shown that they do not arise from instrumental or personal error, and that they bear the predicted relation to the vertical shear of horizontal wind. That the asymmetry is real and not due to errors, can be easily demonstrated, and will be shown in the final paragraphs.

The relation between turbulence distribution and the wind structure will be discussed next. There were 11 separate clouds through which traverses were made. Days were chosen for the observations when the easterly trade regime was nearly uninterrupted [WYMAN and COLLABORATORS, 1946], and the wind showed rather little change in direction or speed with height throughout the cloud layer. In ten of the traverses, the plane was flown on a course within a few degrees of the upwind direction. In the eleventh, the plane was flown nearly at right angles to the wind, and hence even the sign of the vertical shear of the wind-component parallel to the plane course would be very difficult to determine accurately. Hence this case is omitted from the discussion. In nine of the ten remaining cases, the shear with height of the headwind component was clearly positive and differed little from one m/sec per 1000 m. In fact, eight of these nine cases were so similar (except in respect to cloud diameters, for which a mean was taken from maps made from the expedition's cloud photographs) that their measurements have been averaged, and the average presented in Figure 5. In these eight cases, the ascending chimney, according to previous reasoning, should have an upwind component of motion, or in other words, the cloud should be drifting downwind with a speed less than the ambient windspeed. The nature of the observed asymmetry in turbulence is in agreement with this supposition. The relative horizontal velocity between jet and environment, computed with the average rate of mass entrainment for trade cumuli found by STOMMEL [1947] averages only 0.2 m/sec at the height of the traverse. Using the average observed δ of 1000 ft, this means that the cloud fragments require 25 min to dissipate after being pulled out from the ascending chimney. In view of the relatively high humidities in the environment (in accordance with BUNKER and STOMMEL [1947] about 70 per cent), this time appears very reasonable.

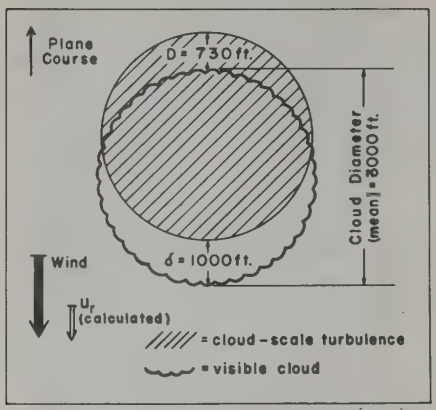

Fig. 5--Average of eight observations of trade cumuli with positive external wind shear (not to scale); note agreement with Figure 4

The two remaining cases are particularly interesting, and further support the major contention of this paper. One of the two was made on the same day and in the same flight as four others which are included in the average shown by Figure 5. It is therefore certain that environment wind structure, relative humidities, and other factors, were identical to those just discussed. This cloud, however, showed no D region at all. Its diameter was far larger than the average flown through, being 15,900 ft. It possessed cloud-scale turbulence (2.3 m/sec) only in the central 7500 ft, with turbulence nearly as low as clear-scale (average 0.67 m/sec) on both edges. Further investigation of the flight records showed pilot reports that this cloud was a towering cumulonimbus from which rain was falling, and therefore much different in structure from the normal trade cumulus. Further evidence that this cloud was in a mature, if not even dissipating, stage came from a computation by the method of STOMMEL [1947] of its rate of mass entrainment. A sounding taken inside this cloud showed, for five successive ten-millibar intervals a negative rate of mass entrainment. Since clearly negative mixing is quite impossible, it is likely that this cumulonimbus was beginning to evaporate in parts. Thus a higher specific humidity could be found in it at successive heights than can be accounted for by any positive mixing between the cloud and its surroundings.

The final case showed a very slight negative shear in the headwind component. The headwind was 13 mph at 1000 ft and 12.2 mph just above the plane at 6700 ft. The asymmetry should therefore, according to theory, be very slight, and reversed in sense from that pictured in Figure 5. Figure 6 shows that this indeed was the case. Greater turbulence than that inside the cloud is found in this case on both outside edges. This bears out a prediction by SCHMIDT [1948] that the ascending jet may often be broader in extent than the visible cloud, the liquid droplets growing in the chimney center. In this case the turbulent region in the clear is broadest, however, on the upwind side in agreement with a calculated, small relative velocity of the cloud downwind.

Possible instrumental or personal errors--From the data presented in the last section, it is already clear that the observed asymmetries in turbulence cannot be due to instrumental errors or lags. This is apparent for three reasons. First, the turbulence is often greater outside than inside the cloud. Second, the asymmetry is not always such that the turbulence (region D) is found only upon the exit of the plane from the cloud (see Fig. 6 for an example). Third, the asymmetry does not occur in every cloud traversed, but seems to be a feature associated with common trade cumulus and was not found in a mature cumulonimbus.

That the results cannot be due to delay in the observer's reaction time, resulting in a late recording of entrance into and exit from the visible cloud is also plain. In general, the cloud was recorded by the observer before turbulence was detected by the instruments and its end marked before the instruments stopped recording cloud-scale turbulence.

As final evidence, a record from the flight accelerometer [VINE, 1945] is reproduced in Figure 7. Since the instrument was very nearly critically damped, two or three complete oscillations of the pen after the turbulence has ceased is completely impossible. Furthermore, the time required after an accelerative pulse for the amplitude to reduce from peak to 1/10 peak value is 0.4 sec. The time during which turbulence of cloud amplitude or greater was observed in the clear outside the cloud edge was six to eight sec. It must therefore be concluded that the asymmetries discussed are real. (Further analysis of each other phase of the instrumentation substantiates the conclusions drawn, but for brevity's sake will not be discussed.)

Acknowledgments--The writer would like to thank Patricia A. Langwell for the use of her analyzed records, data, and files, and for innumerable valuable suggestions and discussions. Thanks are also due to Bernhard Haurwitz for helpful criticisms, and to Andrew F. Bunker,

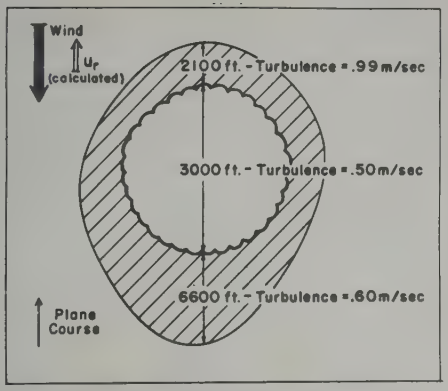

Fig. 6--Single case illustrating trade cumulus accompanied by slight negative external wind shear (not to scale); note reversal of asymmetry as compared with Figure 5; the average value of turbulence measured on this traverse away from the cloud was 0.22 m/sec

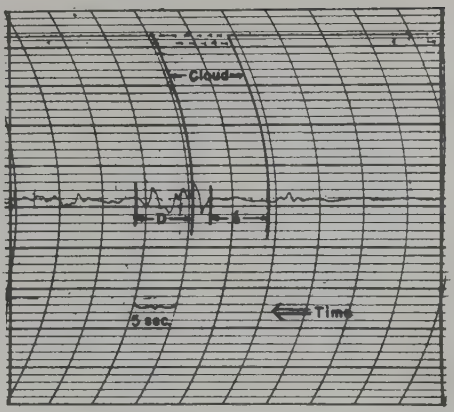

Fig. 7--Actual accelerometer record for one of the cases presented schematically by Figure 5; note time elapsed during passage through regions δ and D; the aircraft was flown at 100 knots airspeed.

Henry Stommel, and Alfred H. Woodcock who participated in many phases of this work. Observational phases of the work have also been discussed with H. R. Byers, Harry Moses, and Chester Newton of the Army-Navy-Weather Bureau Thunderstorm Project. The field work of this project was carried out under contract with the Bureau of Ships of the United States Navy Department and study of the results is being continued under contract with the Office of Naval Research.

References

AUSTIN, JAMES M., A note on cumulus growth in a non-saturated environment, J. Met., v. 5, pp. 103-107, 1948.

BJERKNES, J., Saturated-adiabatic ascent of air through a dry-adiabatically descending environment, Q. J. R. Meteor. Soc., v. 64, pp. 325-330, 1938.

BUNKER, ANDREW F., and STOMMEL, HENRY, Measurements of wet and dry bulb temperature in the lowest 10,000 ft of the atmosphere over the ocean near Coco Solo, Panama, and San Juan, Puerto Rico, Woods Hole Oceanographic Institution, 1947 (unpublished).

BYERS, HORACE R., and BRAHAM, ROSCOE R., JR., Thunderstorm structure and circulation, J. Met., v. 5, pp. 71-86, 1948.

GOLDSTEIN, S. (editor), Modern developments in fluid dynamics, Oxford Univ. Press, two vols,, 1938.

LANGE, KARL O., Thermals at low altitudes, their vertical velocity, size, and origin, Soaring, v. 9, pp. 10-13, 1945.

LANGWELL, PATRICIA A., Inhomogeneities of turbulence, temperature, and moisture in the West Indies trade-wind region, J. Met., v. 5, pp. 243-246, 1948.

ROSSBY, CARL-G., Dynamics of steady ocean currents in the light of experimental fluid mechanics, Papers in Phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole Ocean. Inst., v. 5, pp. 13-18, 1936.

SCHMIDT, F. H., Some speculations on the resistance to the motion of cumuliform clouds, Kon. Netherlands. Met. Inst., Med. en Verhndlngn. Serie B, no. 125, pp. 31-35, 48-52, 1948.

STOMMEL, HENRY. Entrainment of air into a cumulus cloud, J. Met., v. 4, pp. 91-94, 1947.

TOLLMIEN, W., Berechnung turbulenter Ausbreitungsvorgänge, Zs. angew. Math. u Mech., v. 6, p. 468, 1926.

VINE, A. C., Accelerometer for air turbulence measurements, memorandum on file at Woods Hole Oceanographic Institution, August 1945.

WYMAN, J., and COLLABORATORS, Vertical motion and exchange of heat and water between the air and the sea in the region of the trades, Woods Hole Oceanographic Institution, 1946 (unpublished).

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(Communicated manuscript received August 24, 1948; open for formal discussion until July 1, 1949.)

Contribution No. 458

SAMPLING ATMOSPHERIC SEA-SALT NUCLEI OVER THE OCEAN[1]

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Atmospheric hygroscopic nuclei are of primary interest to meteorologists in studies of haze, fog, clouds, etc. (Simpson, 1941; Middleton, 1941; Sheppard, 1947). The sea surface is presumed to be an important source of these nuclei in the form of drops of concentrated sea water arising from spray. Gautier (1899), Jacobs (1939) and others have made measurements of total air-borne chlorides by use of filtering methods; Wright (1940b) and Neiburger and Wurtele (1948) have related changes in visibility and relative humidity to the number and average size of hygroscopic nuclei. However, no information seems to be available which gives the measured weights and numbers of sea-salt nuclei[2] at various heights in clear air over the open sea (see summaries by Landsberg, 1938; Wright, 1940a; Simpson, 1941).

The primary purpose of this paper is to describe the methods used to sample sea-salt nuclei in air over the sea and to measure the weight of chloride[3] in these nuclei. Data are shown giving the weight and number of salt nuclei sampled from aircraft at various heights over the open sea.

The following methods of sampling and measuring air-borne nuclei containing chlorides are modifications of those used by Cunningham (1942). The sampling of aerosols by exposing small glass slides to an air stream has been used by Houghton and Radford (1938), Cunningham (1942), May (1945), Schaefer (1946) and many others. The present authors used 1 x 15 mm glass surfaces cut from microscope slides that were ground to size on a lens-grinding wheel; these slides were cleaned and then coated with hydrophobic Dri-film[4] in the manner

[1] Contribution No. 458 of the Woods Hole Oceanographic Institution. This study was supported by the Office of Naval Research, under contract number N6onr-277TO11.

[2] Hereafter these nuclei, whether in the crystalline or liquid phase, will be termed "salt nuclei" or simply "nuclei."

[3] When chloride, chlorinity or Cl is used, reference is made to chlorine present as chloride or chloride ion.

[4] Dri-film No. 9987, made by the General Electric Co., Schenectady, New York.

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suggested by Langmuir (1944). A Dri-film coating causes drops of water to become hemispheric on the slides, as shown in Fig. 1, where sprayed sea-water nuclei and sampled atmospheric nuclei are seen as crystalline masses and as liquid hemispheres viewed from top and side. In this study it is assumed that the nuclei, when liquid, are hemispheres. Fig. 2A shows the vane used to expose the slides normal to the air stream.

Following exposure, the slides were brought to the laboratory and placed in a lucite box which is mounted upon a microscope stage (Fig. 3). A 50 ml sample of sulfuric acid and water was introduced for vapor pressure control, after which the box was sealed. Temperature was thermostatically controlled. When the temperature of the air around the microscope and that of the acid solution inside the lucite box were equal (within $\pm$ 0.1° C), and when the drops on the slides ceased changing in diameter, it was assumed that the air in the chamber had reached water vapor saturation. The hygroscopic nuclei immersed in this air gain or lose water vapor, thus causing changes in nuclei salt concentration. At the point of equilibrium the water vapor pressure over the nuclei[5] will equal that over the acid solution, which is known. This method, which is an adaptation of a chemical technique for determining the concentration of solutions, is referred to by Glasstone (1940) as the "isopiestic" or equal pressure method.

After equilibrium was established, counts and diameter measurements of the nuclei were made. Since the vapor pressures and densities of concentrated sea water are known, it is possible to determine the weight of the chloride in the individual nuclei.

The weight, in grams, of the total chloride in all of the measured nuclei on a slide (W_{Cl}) is derived as follows:

$$W_{Cl} = V\, d\, Cl\,, \qquad (1)$$

where V = volume of nuclei in μ^3, d = density of nuclei in g/cm^3 and Cl = chlorinity of nuclei expressed as weight fraction. In the equation, volume is computed from nuclei diameters; chlorinity is read from Fig. 5, using the vapor pressure and temperature of the acid solution; acid solution vapor pressures are read from Fig. 6, nuclei densities are

[5] Curvature effects upon vapor pressure over the nuclei are not generally significant when using the above method of determining the Cl present in the nuclei. This is due to the fact that the nuclei, when in equilibrium with a 16% solution of H_2SO_4 + H_2O, are hygroscopic solutions of sea salt with a concentration of Cl about 75 °/$_{oo}$ by weight. In these nuclei small increases in vapor pressure due to surface tension are readily balanced by decreases in vapor pressure produced by small increases in the salt concentration (see Fig. 5).

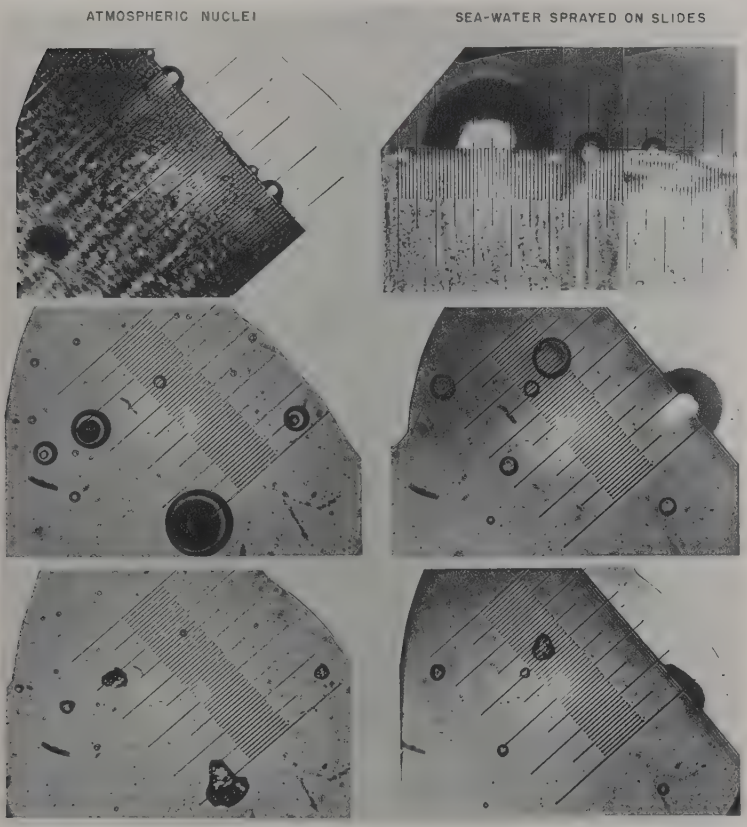

Figure 1. Photomicrographs of sea-water nuclei and sampled atmospheric nuclei as crystalline masses and as liquid hemispheres viewed from the top and side. Scale: one division = 2.2 μ

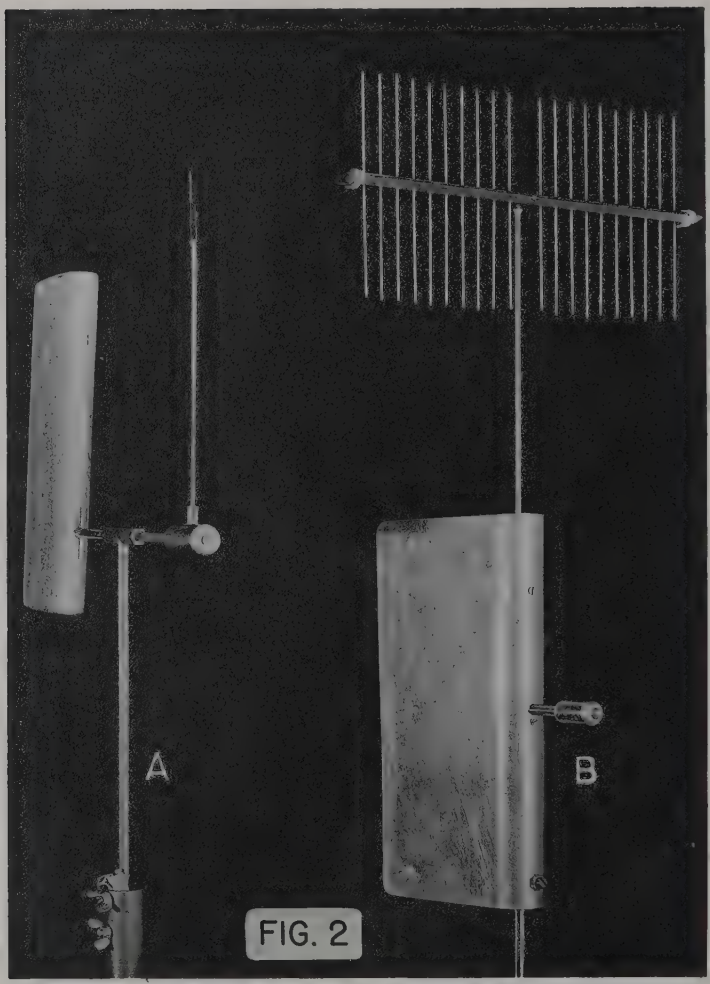

Figure 2. The glass slide and silver rod sampling surfaces and the vanes used to hold them normal to the air stream.

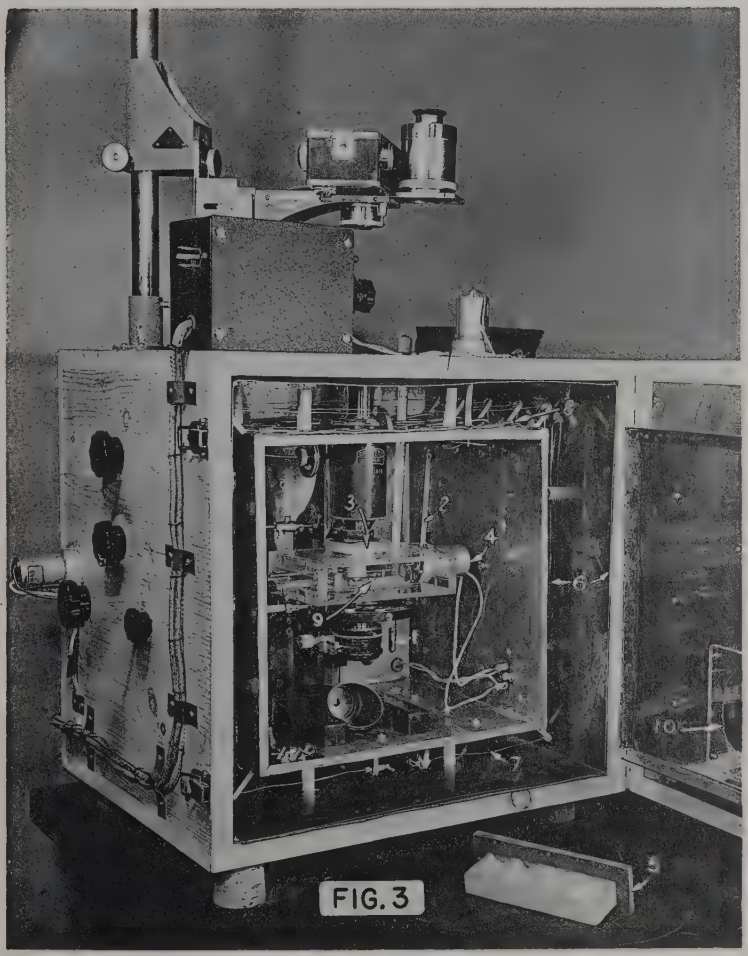

Figure 3. The lucite box and accessory apparatus used to control temperature and water vapor pressure over the nuclei. 1. Thermometer for measuring temperature of ambient air. 2. Thermometer for measuring temperature of vapor pressure control solutions. 3. Rubber diaphragm producing a flexible seal between microscope objective and lucite chamber. 4. Six volt stirring motor. 5. Container for vapor pressure control solutions which is attached to front side of lucite box. 6. Sheet copper boxes to facilitate uniform distribution of temperature. 7. Heating wires for temperature control (power source: 6 volt battery). 8. Thermometer tube of temperature control device. 9. Stage for glass slides. 10. Double lucite window in housing door for admitting light.

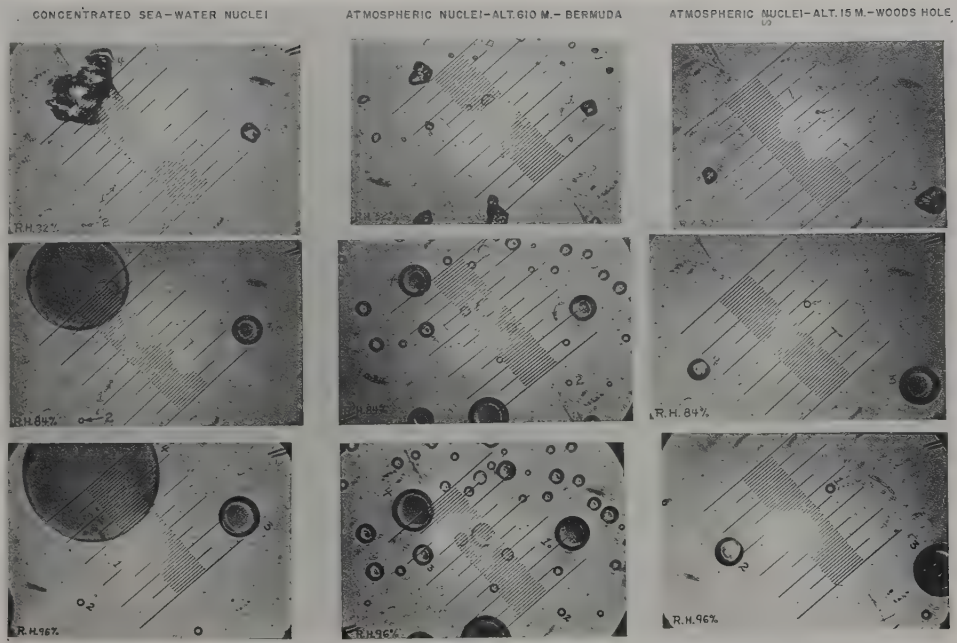

Figure 4. Photomicrographs showing changes in the appearance of nuclei as the relative humidity is increased. The nuclei at the left were sprayed on the slide. One div = 2.2 μ

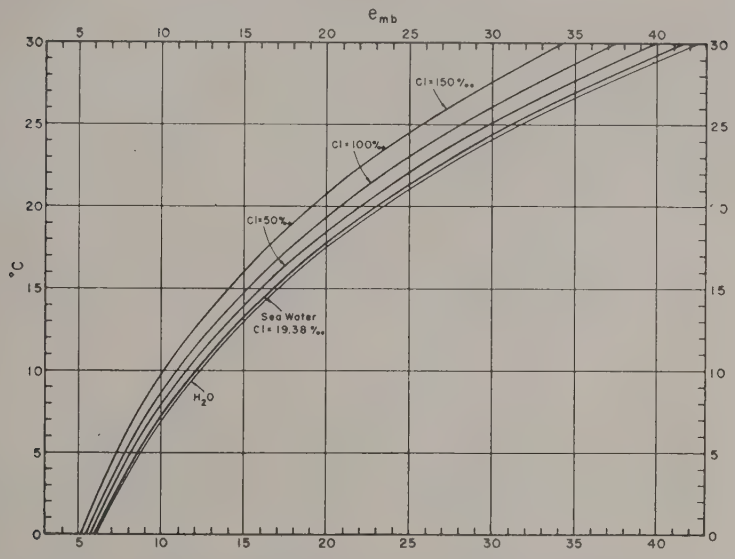

Figure 5. Saturation vapor pressure over water, sea water and concentrated sea water. Sources of data for this graph: Vapor pressure over water, from table 79 in Smithsonian Meteorological Tables; vapor pressure over sea water, from table 29 in Sverdrup, et al., 1942: 116; vapor pressure over concentrated sea water, from table 6 and chart 3 in Higashi, et al., 1931: 171, 172.

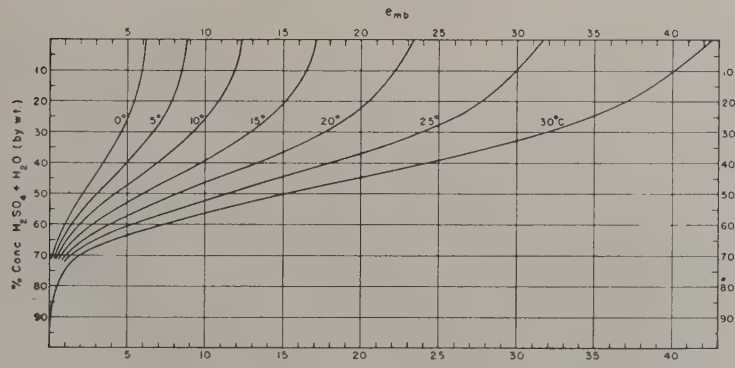

Figure 6. Water vapor pressure over solutions of $H_2SO_4 + H_2O$ (from International Critical Tables, vol. III: 302).

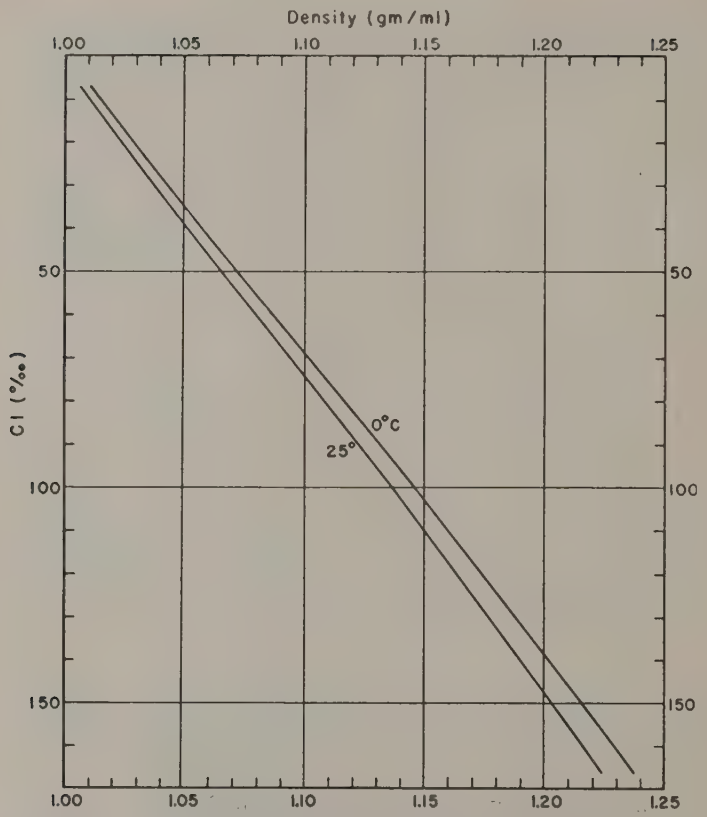

Figure 7. Density of concentrated sea water (from Higashi, et al., 1931).

read from Fig. 7. The sources of the information on these graphs are indicated below them.

I. What is the accuracy of this isopiestic method when it is used to determine the chloride content of seawater drops which are sprayed on the slides? II. Are the hygroscopic nuclei, which deposit on the slides in marine air, composed of concentrated sea water? These questions will be discussed in this order.

I. The accuracy of the isopiestic method was tested as follows. Sea water was sprayed on several slides, which were then placed in the control chamber under the microscope; the chloride content was determined over an acid solution and over sea water as well. The slides were then removed from the chamber and placed in a test tube containing water. The dissolved salts were titrated for chlorides, using the Oxner (1920) silver nitrate method.[6] Table I shows the

TABLE I. Comparison of the Nuclei *Cl* Content as Determined by Direct Titration and by a Modification of the Isopiestic Method

*No. of nuclei measured**	*Total Cl on slides by the isopiestic method*		*Cl by titration of solution of all nuclei on slides*	$\frac{C-A}{C}$	$\frac{C-B}{C}$
	A *e control with* 16% $H_2SO_4 + H_2O$ *solution*	*B* *e control with sea water*	*C*		
160	4.1×10^{-4} gms.	——	3.5×10^{-4} gms.	−.171	——
565	2.1×10^{-4} gms.	1.5×10^{-4} gms.	2.0×10^{-4} gms.	−.050	.25
586	2.9×10^{-4} gms.	2.0×10^{-4} gms.	2.6×10^{-4} gms.	−.115	.23

* These *Cl* values are based upon diameter measurements of the nuclei deposited on about 1% of the total area over which the sea-salt nuclei were sprayed. The assumption is made that the nuclei thus measured are a representative sampling of the nuclei over the total surface.

results of three of these experiments. Computed chloride values are given in columns A and B, titrated values in column C and percent errors in the last columns. Titration values are assumed to be correct.

Thus the isopiestic method can be used to measure the chlorides in concentrated seawater drops with an accuracy of about ± 20%.

II. In regard to the chlorinity of nuclei which are sampled over the sea, the first experiment, indicating that the nuclei sampled in marine air are concentrated sea water, is qualitative in nature. Fig. 4 shows photomicrographs of nuclei at different indicated R.H. values; these pictures were selected because of the large range of drop diameters shown. The nuclei in the pictures at the left are concentrated sea water, those in the middle show nuclei sampled near Bermuda, and those on the right are of nuclei from the Woods Hole area. All nuclei are crystalline at an R.H. of 32%. At the higher R.H. values shown all nuclei are liquid, their diameters increasing with increasing R.H. In Fig. 8 are shown radii changes of the numbered nuclei in Fig. 4. The changes in radii of the atmospheric nuclei are similar to those of

[6] The accuracy of the Oxner method for titrating these small quantities of chloride was found to be ± 10%.

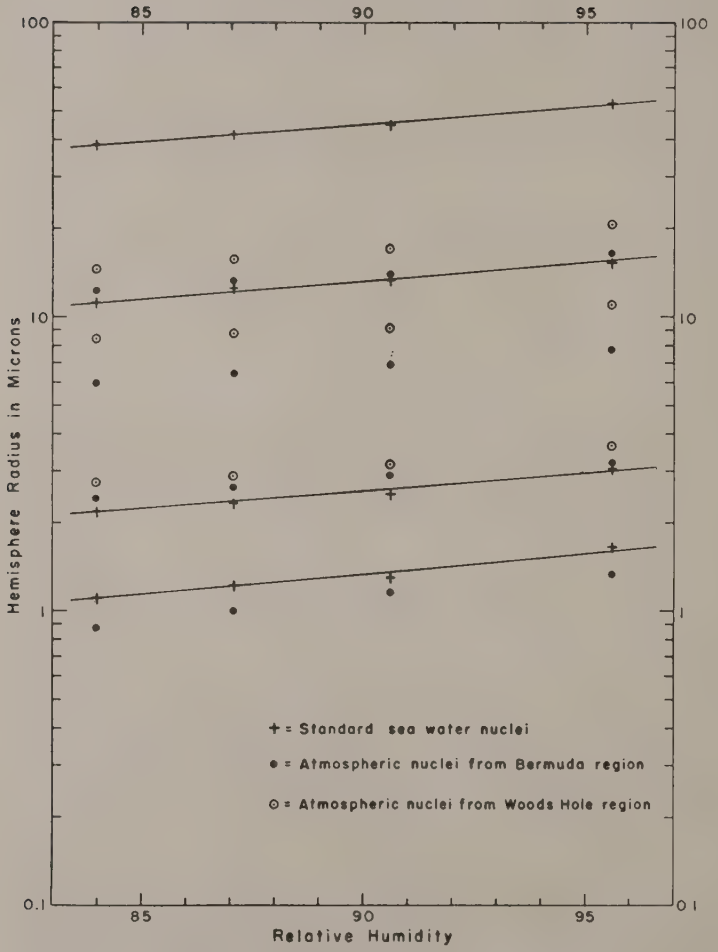

Figure 8. Changes of nuclei radii occurring as the relative humidity is increased.

the known seawater nuclei. Thus these nuclei are similarly hygroscopic and all show crystalline masses[7] at the low R.H. values.

A more quantitative method of indicating the nature of these airborne nuclei will now be described. Hard-drawn silver rods, 1 mm square, were exposed to the air at the end of a dock in Woods Hole (see Fig. 2B). These rods were usually exposed during the passage of about 100,000 meters of air, and glass slides were exposed beside the silver rods to about 2,000 meters of air. Three slide samples were taken—at the beginning, near the middle and at the end of the period of exposure of the silver rods. After exposure, the salt-encrusted silver rods were placed in water, and the dissolved salts were then titrated for chlorides. (Deposition of nuclei on the side and rear surfaces of the rods was not significant.) The samples taken on the glass slides were measured by the isopiestic method. Table II shows

TABLE II. A Comparison of the Chloride Content of the Air, as Determined by the Isopiestic and Titration Methods. Sampling Height 4 Meters over the Sea Surface. Location: the Seaward End of the Marine Biological Laboratory Dock, Woods Hole, Massachusetts

Date	*Wind Velocity*	*Total nuclei measured on three slides*	R_l*	*A* *Av. Cl by isopiestic method* (g/cm^3 *of air*)	*B* *Cl by titration of a solution of nuclei from silver rods* (g/cm^3 *of air*)	$\frac{B-A}{B}$	R_{Cl}†
VI.14.48	4.9 m/s SW	458	.06	0.54×10^{-12}	1.05×10^{-12}	+.49	.46
VI.17.48	6.3 m/s SW	883	.05	1.17×10^{-12}	1.51×10^{-12}	+.23	.42
VI.18.48	5.3 m/s SSW	426	.03	0.55×10^{-12}	0.68×10^{-12}	+.28	.14
VI.30.48	7.6 m/s SW	1532	.03	2.73×10^{-12}	2.72×10^{-12}	0	.80

* R_l = Ratio of total exposure length of three glass slides to exposure length of silver rods.

† R_{Cl} = Ratio of minimum value to maximum value for atmospheric chlorides measured by the glass-slide isopiestic method.

the results of these measurements; column A gives the average chloride computed from the drops on the three slides, column B the values for chloride in the nuclei deposited upon the silver rods, the next to last column the percent error of the glass-slide isopiestic method, assuming

[7] It may be supposed that crystalline nuclei will fail to adhere to the glass slides upon impact, thus producing unknown errors in this method of sampling. It is probable, however, that the presence of the highly soluble magnesium and calcium chlorides in sea salt will cause crystalline material of lower solubility in a nucleus to remain wet at relative humidities as low as 33% (see International Critical Tables, Vol. 3: 367, 368 for vapor pressures over saturated aqueous solutions of $MgCl_2$ and $CaCl_2$). For this reason it is assumed here that crystalline sea-salt nuclei, at relative humidities above about 30%, will adhere to the glass slides upon impact as readily as they do when completely liquified.

that the titration values are correct. The difference between the two methods is not great in consideration of the small quantities measured and of the rather large maximum variations of chloride shown by the individual slides (see column R_{Cl}). The largest percent error, 0.49, is attributed to these variations within the air stream. (The relatively short exposure lengths of the slides, indicated by column R_l, were used in order to measure the size distribution of the nuclei, as it was not thought at the time that there would be so much variability of salt content within the air stream.)

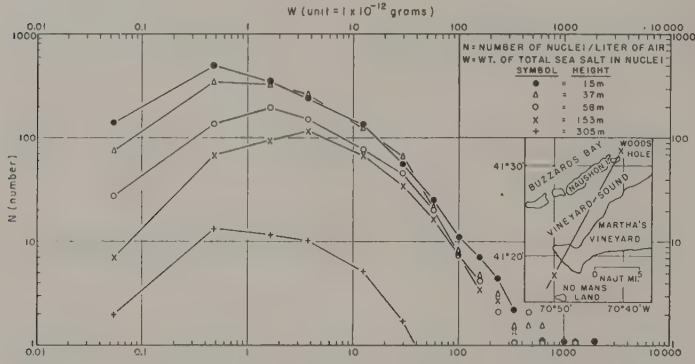

Figure 9. The numbers and weights of sea-salt nuclei sampled in the lower atmosphere over the sea (see Table III for position, time, etc.).

Thus the isopiestic method indicates a chlorinity of atmospheric nuclei approximately the same as the chlorinities derived by titration of deposited salts. The method also indicates that the atmospheric nuclei are similarly hygroscopic when compared to concentrated sea-water nuclei, and show similar crystalline masses at low R.H. values. Therefore, the isopiestic method seems useful in measuring the weights and numbers of atmospheric nuclei which are sampled.

Fig. 9 shows the numbers and weights of nuclei that were sampled from an aircraft in air which had passed over about 150 miles of sea surface. The lines are added to aid the eye in following the trend of the observed points. The weights of the nuclei represent the total sea salts present, assuming that the total salts are equal to 1.805 × chlorinity, expressed as parts per thousand by weight. Each set of symbols represents the weight and number distribution at some specified height. (The weight of the smallest nucleus shown is based

upon an estimated drop diameter.) The "X" mark on the insert chart shows the location of the sampling area.

Fig. 10 shows the data in Fig. 9 corrected for deposition error; that is, correction has been made for the fact that some of the air-borne

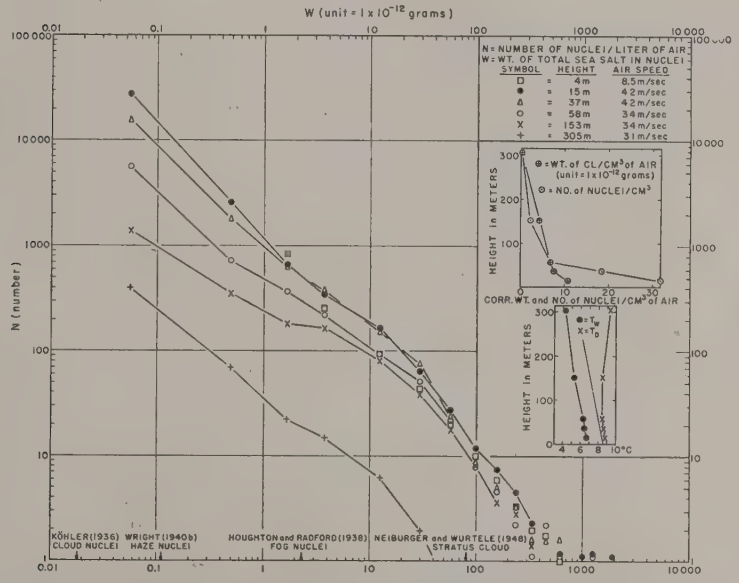
W (unit = 1 x 10⁻¹² grams)
N (number)
N = NUMBER OF NUCLEI / LITER OF AIR
W = WT. OF TOTAL SEA SALT IN NUCLEI
SYMBOL HEIGHT AIR SPEED
□ = 4m 8.5m/sec
● = 15m 42m/sec
Δ = 37m 42m/sec
○ = 58m 34m/sec
X = 153m 34m/sec
+ = 305m 31m/sec
⊕ = WT. of CL/CM³ of AIR (unit = 1 x 10⁻¹² grams)
⊖ = NO. of NUCLEI/CM³
HEIGHT in METERS
CORR. WT. and NO. of NUCLEI/CM³ of AIR
⊕ = T_w
X = T_D
°C
KÖHLER (1936) CLOUD NUCLEI
WRIGHT (1940b) HAZE NUCLEI
HOUGHTON and RADFORD (1938) FOG NUCLEI
NEIBURGER and WURTELE (1948) STRATUS CLOUD

Figure 10. The data in Fig. 9 corrected for deposition error (E). The square symbols represent the corrected deposition of nuclei on two slides exposed at wind speed before and after the airplane samples were taken. Above the lower *W* scale are shown the average or mean values for sea-salt nuclei weight as derived by various authors.

nuclei are deflected by the flow of air around the slides and hence fail to impinge upon them, This error, for the very small nuclei, is large, and there is some uncertainty as to its magnitude for the smallest nucleus shown. The inserts in Fig. 10 show variations with height of air temperature and of nuclei weight and number. Table III shows other information concerning the data in Figs. 9 and 10.

For correction of deposition error, reference was made to a mathematical study by Langmuir and Blodgett (1945) on water droplet trajectories and deposition. They found the maximum total efficiency of drop deposition on ribbons, assuming ideal fluid flow. Drop

TABLE III. Additional Data Relative to Atmospheric Nuclei Measurements Shown in Figs. 9 and 10. Date, April 30, 1948. Position, Latitude 41° 18′ N., Longitude 70° 50′ W. Surface Wind, Force 4, Direction SW. Probable Fetch, < 200 Nautical Miles. Atmospheric Pressure 1002 to 1006 mb. Sky, Clear

1	2	3	4	5	6	7	8		9		10		11
Time (EDT)	*Height (m.)*	*Air speed (m/sec)*	T_D*	T_W*	e_{mb}	*R.H.*	*Cl in g/cm³ of air. Unit = 1 × 10⁻¹²*		*No. of nuclei per cm³ of air*		*Covering fraction*		*No. of*
							uncor.	*cor.*	*uncor.*	*cor.*	*nuclei cryst.*	*nuclei Cl conc. 7%*	*nuclei counted*
1350†	4	9	9.9	8.8	10.5	86	2.98	5.01	0.16	1.2	——	0.009	386
1500	15	42	8.8	6.7	8.4	74	9.07	10.93	1.48	31.9	0.004	0.023	662
1508	37	42	8.7	6.5	8.2	73	6.1	7.77	1.25	18.6	0.005	0.029	795
1515	58	34	8.5	6.4	8.2	73	5.43	6.82	0.68	7.1	0.004	0.025	635
1520	153	34	8.5	5.3	6.9	62	3.56	4.44	0.43	2.3	0.004	0.024	612
1528	305	31	9.4	4.3	5.0	42	0.12	0.23	0.045	0.5	0.001	0.003	516
1740†	4	8	9.5	8.7	10.7	90	5.92	8.3	0.19	1.4	——	0.013	456

* All T_D and T_W measurements made from aircraft were read from sling psychrometer thermometers held in the air stream. Correction for temperature rise due to dynamic heating on the dry bulb (ΔT_d) and the wet bulb (ΔT_w) is approximated (from Spilhaus, 1943) as follows:

$$\Delta T_d = a_d \left(\frac{V}{100}\right)^2$$

and

$$\Delta T_w = a_w \gamma \left(\frac{V}{100}\right)^2,$$

where a_d and a_w depend upon the form of the thermometers and γ is the ratio of the wet to the dry lapse rates. A value of 0.85 is used for both a_d and a_w.

† At this time slides were exposed at the end of a dock in Woods Hole. These samples were taken before and after the flight on which the other samples were obtained.

deposition efficiencies (E) are given in terms of two dimensionless parameters K and Φ, which are defined in the following equation:

$$K = \frac{2\rho s\, a^2 U}{9\eta_l C}, \tag{2}$$

and

$$\Phi = \frac{18\rho a^2\, CU}{\eta \rho s},$$

where a = drop radius in cm, ρa = air density in g/cm³, ρs = drop density in g/cm³, η = viscosity of air in poises (g/cm sec), C = ½ width of slide in cm, and U = wind speed in cm/sec.

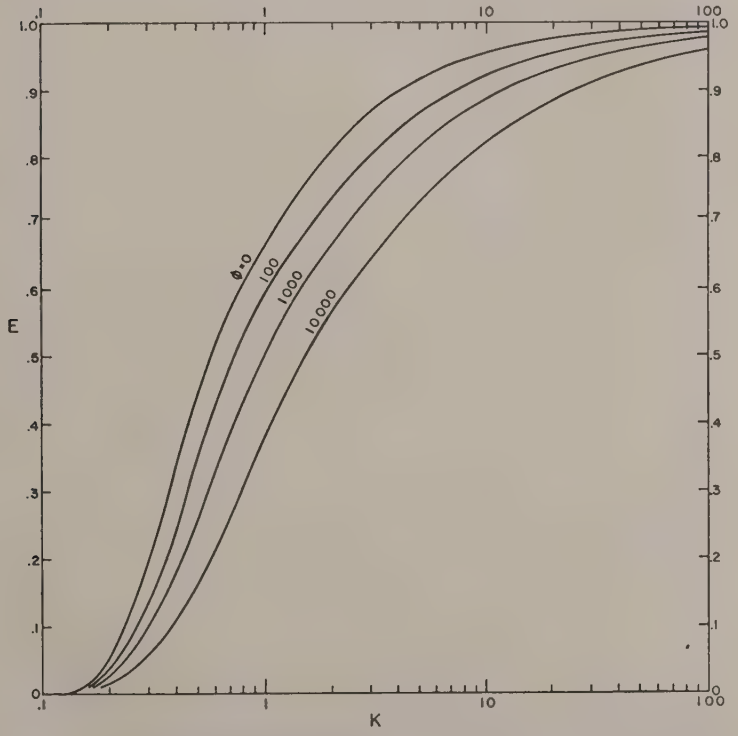

Figure 11. Efficiency of rime deposition on ribbons with ideal fluid flow (from Langmuir and Blodgett, 1945).

Constant values for drop density, air density, air viscosity and width of ribbon were substituted in these equations, leaving drop radius and wind speed as the two variables. Wind speed was fixed arbitrarily, while Φ and K were calculated for drop radii varying from 0.3 to 14 microns. Deposition error (E) was then taken from the results of Langmuir and Blodgett (see Fig. 11), using the Φ and K values

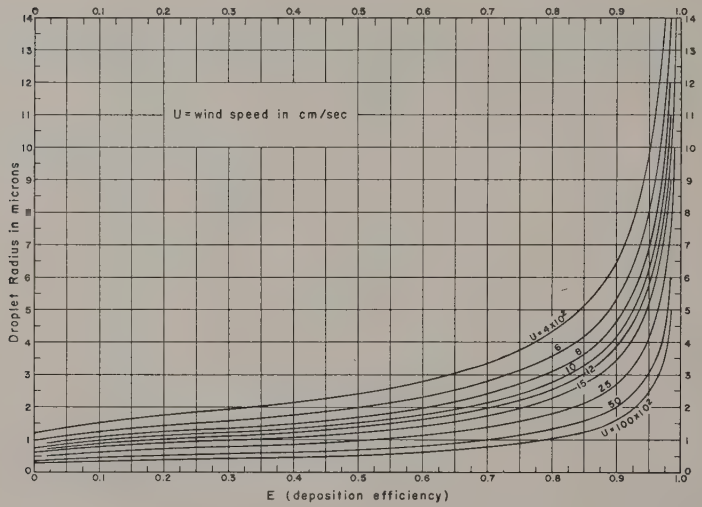

Figure 12. Deposition efficiency of water droplets upon "ribbons" one millimeter wide (Langmuir and Blodgett, 1945).

derived from the equations. This process was carried out for wind speeds ranging from 4 to 100 m/sec. The results are plotted in Fig. 12, which can be used in deriving E for nuclei samples taken in an air temperature range of 0° to 25° C., with a maximum error in E of 3%.

A nuclei density of one was used in deriving the E values plotted in Fig. 12. To avoid separate calculations and curves for the deposition efficiency of nuclei of varying densities, a simple correction may be applied to Fig. 12 for those cases where nuclei density is significantly different from one. The equations for K and Φ, and the family of curves for K, Φ and E (see Fig. 11), indicate that proportionate changes of density or wind speed affect the resulting computed value

of E similarly. Thus, doubling the value of ρ_s gives about the same value of E as does the doubling of U. As a specific example of the use of Fig. 12, assume that nuclei of 1 μ radius are sampled at an air speed of 30 m/sec and at a time when their density in the free air is 1.2 [see equation (3) for the method used to derive nuclei radii in the free air]. In this case the modified value for air speed is 1.2 $\times$ 30, or 36 m/sec. A nucleus of 1 μ radius which was sampled on a 1 mm wide ribbon and at a modified air speed of 36 m/sec has a deposition efficiency of about 0.6 (see Fig. 12).[8]

The radius (R) of the nuclei in the free air at the time of sampling is derived as follows:

$$R = \sqrt[3]{\frac{W}{\frac{c\,D}{4/3\pi}}} \quad . \tag{3}$$

W = the weight of chloride in the nucleus (unit = 1×10^{-12} g). c = nucleus chloride concentration by weight fraction; taken from Fig. 5, using the dry-bulb temperature and the vapor pressure of the free air where the samples were taken.[9] D = nucleus density in g/cm^3; taken from Fig. 7, using the dry-bulb temperature of the air in which the samples were taken and the nucleus concentration derived above.

It has been necessary to discuss deposition error at this time in order to point out the errors of impact sampling.

Are nuclei of the weights and numbers which were sampled at air speeds up to 42 m/sec actually present in the air? Is it not possible that coalescence or shattering may have altered the nuclei weight and number distribution?

Langmuir (1944) has shown that coalescence of cloud and fog drops, upon impact on glass slides, may modify significantly the size distribution when the covering fraction (i. e., the per cent of the slide surface covered by the drops) exceeds 0.1. A direct test for possible coales-

[8] For the ranges of sampling speed, nuclei radii and nuclei density discussed in this paper, the above method of allowing for the variation of nuclei density produces a value of E which is correct to within 3%.

[9] In those cases where the free air humidity is between 78 and 70%, chloride concentration is derived by extrapolation of the results of Higashi et al. (1931) (Fig. 5). Below a humidity of 70% it is assumed that the nuclei are mostly crystalline (from Owens, 1926) with a density of about 2.2. In deriving deposition error E it is also assumed that these crystalline nuclei deposit on the slides as would spherical droplets of the same density (see footnote 7).

cence and shattering was made at an R.H. of 82%, when the nuclei are always liquid.

Six glass slides were exposed at constant altitude over the sea—three at higher and three at lower air speeds. Fig. 13 shows the distribution of weights and numbers of the nuclei sampled. It can be

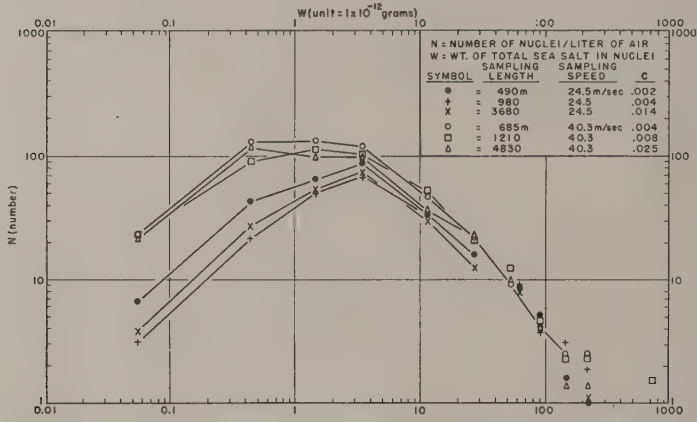

Figure 13. Variations of nuclei weight and number with different sampling lengths and speeds (see Table IV for further data).

seen on this slide that there is little difference in the numbers and weights of nuclei sampled on three slides of increasing covering fraction (C) exposed at a speed of 24.5 m/sec (see the lower plotted symbols). Similarly, Fig. 13 shows little difference in the number and weight of nuclei sampled at an air speed of 40.3 m/sec.

If a significant amount of coalescence of nuclei had occurred at constant air speed, Fig. 13 should show an increasing proportion of larger nuclei and a decreasing proportion of smaller nuclei associated with increasing values of C. Fig. 13 shows no trend towards larger nuclei which is related to increasing covering fraction. It is concluded as improbable, therefore, that coalescence of nuclei was a significant factor in producing the weight range shown.

Do the nuclei become shattered by impact? Fig. 13 indicates an increase in the numbers of nuclei sampled with a speed increase. Differences in deposition efficiency account for much of this discrepancy in number. In Fig. 14 are plotted average N values (from

Fig. 13) to which the deposition error correction has been added. The remaining difference in the average N at the two sampling speeds is attributed to changes, between sampling periods, in the amount of chlorides present in the air, as shown in Table IV. Note that the

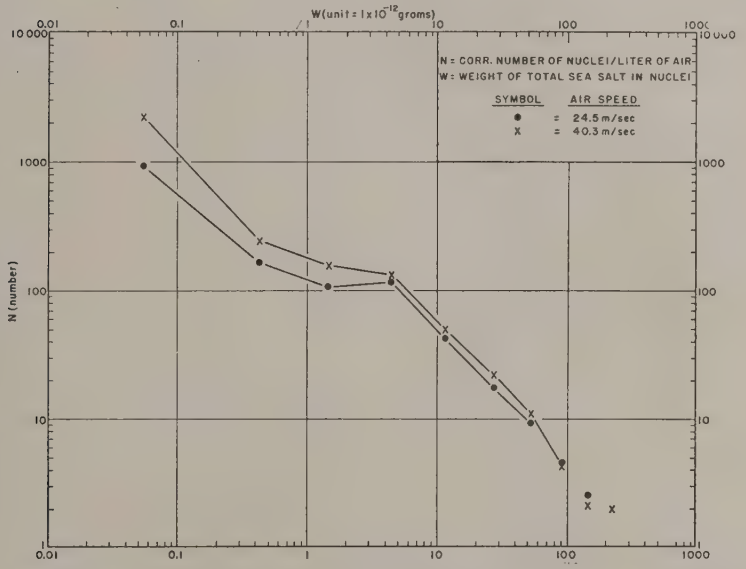

Figure 14. Average N values, from Fig. 13, which have been corrected for deposition error.

largest values in column 8, corrected and uncorrected, correspond to the higher air speed (column 2). This change can be due to variations of N with time or to slight variations in sampling height.

Shattering tests have also been made when nuclei are crystalline, at an R.H. of 43%. No shattering has been observed.

The sampling results which have been shown and discussed indicate that neither coalescence nor shattering of nuclei upon impact is a significant factor in the production of the nuclei weight and number distributions shown. This conclusion gains further support from the similarity of the corrected deposition of nuclei on slides exposed at an average wind speed of 8.5 m/sec and at 42 m/sec (see Fig. 10). The square symbols represent samples taken near the surface at Woods

TABLE IV. Data Relative to a Test of the Effects of Air Speed and Exposure Length Upon the Weight and Number Distribution of Nuclei Deposited on Glass Slides (see Fig. 13). Date, June 25, 1948. Position, Latitude 41° 18′ N., Longitude 70° 50′ W. Surface Wind, Force 3, SW. Atmospheric Pressure, 1006 mb. Time, 1700 to 1720 EDT

1	2	3		4	5	6	7	8		9	10	11
Height (m)	*Air speed*	*Slide exposure length in:*		T_D	T_W	e_{mb}	*R.H.*	*Cl per cm³ of air. Unit = 1 × 10⁻¹² g*		*No. of nuclei per cm³ of air uncorrected*	*Covering fraction (%)*	*No. of nuclei counted*
		sec	*m*					*uncor.*	*cor.*			
15	24.5	20	490	18.75	16.75	17.6	82	2.92	3.48	.26	.002	517
15	24.5	40	980	——	——	——	——	3.14	3.60	.21	.004	558
15	24.5	150	3680	——	——	——	——	3.16	3.62	.22	.014	581
15	40.3	17	685	——	——	——	——	4.42	5.00	.49	.004	597
15	40.3	30	1210	——	——	——	——	6.66	7.26	.43	.008	563
15	40.3	120	4830	——	——	——	——	4.25	4.74	.41	.025	608
61	24.5	——	——	23.35	18.05	17.0	60	——	——	——	——	——
2*	4	60	240	17.9	17.5	19.5	95	78.0	——	——	——	544

* These measurements were made on a beach two nautical miles downwind from the sea position given above. Nuclei produced by the local surf probably account in large part for the increase in *Cl* per cm³ of air as shown by this beach sample (see column 8).

Hole after the lower air had been mixed in passing over small islands (see insert, Fig. 9). The close agreement is evident. Sea fog nuclei, sampled at 7 m/sec, also show a closely similar distribution in the weight range of 5×10^{-12} g and less, again indicating the presence of the smaller salt nuclei in the sea air. (Sea fog nuclei samples from the Woods Hole area have indicated thus far that sea salt is the nucleus upon which fog drops form.)

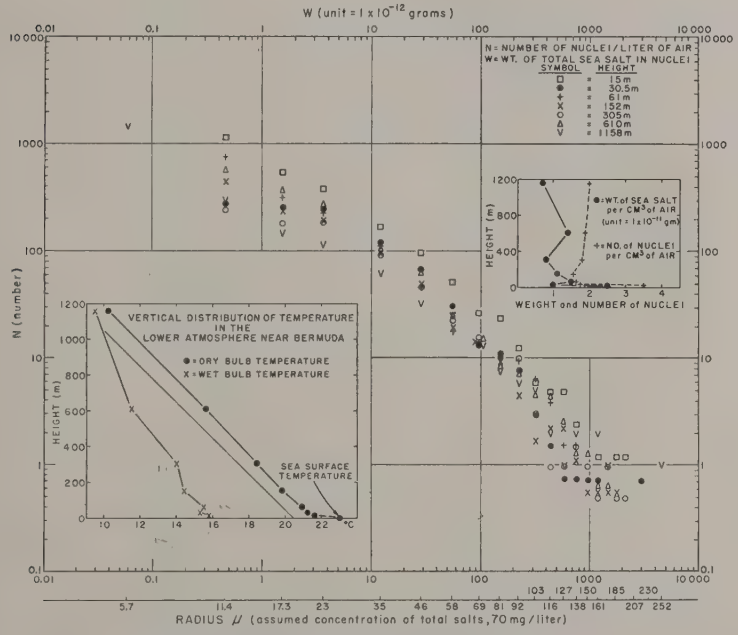
W (unit = 1 x 10⁻¹² grams)
N = NUMBER OF NUCLEI / LITER OF AIR
W = WT. OF TOTAL SEA SALT IN NUCLEI
SYMBOL HEIGHT
15 m
30.5 m
61 m
152 m
305 m
610 m
1158 m
N (number)
HEIGHT (m)
WEIGHT and NUMBER of NUCLEI
●=WT. of SEA SALT per CM³ of AIR (unit = 1 x 10⁻¹¹ gm)
+=NO. of NUCLEI per CM³ of AIR
VERTICAL DISTRIBUTION OF TEMPERATURE IN THE LOWER ATMOSPHERE NEAR BERMUDA
●=DRY BULB TEMPERATURE
X=WET BULB TEMPERATURE
SEA SURFACE TEMPERATURE
°C
RADIUS μ (assumed concentration of total salts, 70 mg/liter)

Figure 15. The numbers and weights of sea-salt nuclei sampled in the lower atmosphere over the sea in the Bermuda area (see Table V for additional information).

Finally, Fig. 15 shows the corrected weight and number of nuclei sampled near Bermuda in air which had passed over at least 600 miles of sea surface. Table V shows further data from this area.

It is interesting to compare the vertical distribution of weight and number of nuclei in the mixed air near Bermuda with the vertical distribution of weight and number of nuclei in thermally stable air near Woods Hole (Fig. 10). In the thermally stable air the total

TABLE V. Data Concerning Air-borne Sea-salt Samples Taken Near Bermuda on November 26, 1948. Position, Latitude 32° 23′ N. Longitude 64° 55′ W. Surface Wind N, Force 3 to 4. Clouds 2 cu.

1	2	3	4	5	6 T†		7	8	9		10		11	12
Time (zone 5)	*Height* (m)	*Slide exposure* (secs)	*Atmos-pheric pressure*‡ (mb)	*Air speed*ø (m/sec)	T_d	T_w	e_{mb}	*R.H.*	*Sea salt in g/cm³ of air; unit* = 1×10^{-12} uncor.	cor.	*No. of nuclei per cm³ of air* uncor.	cor.	*Covering fraction* (%)	*No. of nuclei measured*
1535	15.2	30	1016.5	31.8	21.6	15.75	10.80	42	30.6	34.6	.70	2.5	.004	738
1540	30.5	60	1015	26.8	21.2	15.30	10.43	42	15.1	17.2	.409	1.0	.004	580
1546	61	60	1012	26.8	20.9	15.5	11.23	45	14.1	16.3	.407	1.5	.004	552
1555	152	120	1000	26.8	19.8	14.4	10.42	45	13.5	15.3	.34	1.1	.006	640
1603	305	120	983	26.8	18.4	14.0	11.45	54	16.0	18.0	.313	0.8	.007	670
1612	610	120	946	26.8	15.6	11.5	10.28	58	16.8	19.3	.44	1.4	.008	723
									*19.8	20.1	.54	.7		
1620	1158	60	883	31.3	10.2	9.5	11.46	92	19.8	20.2	.69	2.1	.093	667

‡ Sea level pressure (1018 mb) was recorded at the Meteorological Office in Hamilton, Bermuda, at 1600. Pressures at other heights are based upon the U. S standard atmosphere.

ø Altitude correction of indicated air speed was not applied. At a height of 1158 m this correction amounts to about 2.1 m/sec. At lower altitudes it is not significant.

† T_d and T_w values are corrected for dynamic heating of thermometers.

* The upper of the two values in columns 9 and 10 (alt. 1158 m.) does not include the smallest nuclei sampled at this height. These upper figures should be used for comparison with values obtained at lower altitudes, since the range of nuclei weight is the same. The lower value includes the smallest nuclei sampled. The deposition of smaller nuclei at the 1158 m. height (see Fig. 15) results from an increase in deposition efficiency with increasing nuclei radii associated with higher R.H. values.

number and total weight of sea-salt nuclei decreased rapidly with height. Near Bermuda, in well mixed air overlying warmer water, there is relatively little change with altitude in nuclei number and weight (see inserts, Fig. 15). This difference in vertical distribution of nuclei is probably a result of the difference in vertical mixing in the two air masses concerned.

At the base of Fig. 15 a second scale is drawn showing the computed radii of the nuclei, assuming spherical drops with a concentration of sea salt of 70 mg/l (7×10^{-17} g/μ^3). In each case the radius indicated is that of a nucleus containing a weight of sea salt equal to the weight of the sea salt in nuclei actually sampled. The concentration of 70 mg/l is the average value given by Houghton and Radford (1938: 30) for the total salt content of fog water at Round Hill, Mass. This concentration is much greater than the average of the figures given by Wright (1940a) in his summary of the measurements which have been made of the chloride concentration of snow, rime, rain and cloud waters. Therefore, a concentration of 70 mg/l seems a conservative figure for salt concentrations in marine cloud drops. The computed drop sizes, based upon this concentration, are therefore assumed to be a reasonable approximation of the eventual cloud drop sizes resulting from the lifting of the air containing these nuclei. Cloud drops having the radii shown at the base of Fig. 15 will have rates of fall varying from about 0.3 to 200 cm/sec (see Humphreys, 1940: 280). Drops of the larger sizes (radius 50 μ or more) are classified as mist, drizzle or light rain by Humphreys.

Thus this great range of nuclei weight at the base of an oceanic cloud, if it proves to obtain generally over the seas, may explain the occurrence of rain from thin layers of stratus clouds ($T > 0°$ C.) in oceanic areas (Kotsch, 1947; Schaefer, 1949).

Acknowledgment of valuable aid in carrying out this work is due R. M. Cunningham, J. S. Coles, Irving Langmuir, W. S. von Arx and Henry Stommel. Instrumentation is due, in major part, to Robert G. Walden and Kenneth G. McCasland.

SUMMARY

A method of sampling air-borne sea-salt nuclei over the open ocean is described. Data are given showing the distribution of the weight and number of nuclei sampled at various heights. It is suggested that these sea-salt nuclei act as condensation nuclei in the formation of sea fogs and clouds, and that the presence of the larger nuclei at cloud bases may account for the production of rain from small clouds in marine locations at temperatures above 0° C. The range of the

weights of these nuclei is comparable to the range of the average weights of salt nuclei which have been measured at shore stations by other authors.

REFERENCES

Cunningham, R. M.
1942. Investigation of the production of condensation nuclei from the sea surface. B.S. thesis, Mass. Inst. Tech., Cambridge. (Unpublished)

Gautier, Armand
1899. Quantité maximum de chlorures contenus dans l'air de la mer. Bull. Soc. chem. Paris, (3) *21:* 391–392.

Glasstone, Samuel
1940. Text-book of Physical Chemistry. D. Van Nostrand Co., Inc., New York. 1289 pp.

Higashi, K., K. Nakamura and R. Hara
1931. The specific gravities and the vapor pressures of the concentrated sea water at 0–175° C. J. Soc. chem. Ind. Japan, *34:* 166–172 (Abstr. 72B).

Houghton, H. G. and W. H. Radford
1938. On the measurement of drop size and liquid water content in fogs and clouds. I. Microscopic measurement of the size of natural fog particles. Pap. phys. Oceanogr. Meteorol., *6* (4)*:* 1–18.

Humphreys, W. J.
1940. Physics of the Air. 3rd ed. McGraw-Hill Book Co., Inc., New York. 676 pp.

Jacobs, W. C.
1939. Apparatus for determining the salt content of the air. Bull. Amer. met. Soc., *20,* 38–42.

Köhler, Hilding
1936. The nucleus in and the growth of hygroscopic droplets. Trans. Faraday Soc., *32:* 1152–1161.

Kotsch, W. J.
1947. An example of colloidal instability of clouds in tropical latitudes. Bull. Amer. met. Soc., *28:* 87–89.

Landsberg, H.
1938. Atmospheric condensation nuclei. (Gerlands) Beitr. Geophys., Sup. III: 155–252.

Langmuir, Irving
1944. Super-cooled water droplets in rising currents of cold saturated air. Gen. Elec. Res. Lab. Rep., A. T. S. C. Contract N-33-106-sc-65. Precipitation static studies. pp. 1–91.

Langmuir, Irving and K. B. Blodgett
1945. A mathematical investigation of water droplet trajectories. Gen. Elec. Res. Lab. Rep., A. T. S. C. Contract W-33-038-AC-9151. pp. 1–47.

May, K. R.
1945. The cascade impactor: An instrument for sampling coarse aerosols. J. sci. Instrum., *22:* 187–195.

Middleton, W. E. K.
1941. Visibility in Meteorology. The University of Toronto Press, Toronto Canada. 165 pp.
Neiburger, M. and M. G. Wurtele
1948. On the size of particles in haze, fog and stratus of the Los Angeles region. Dept. of Meteorology, Univ. of California at Los Angeles (Unpublished).
Owens, J. S.
1926. Condensation of water from the air upon hygroscopic crystals. Proc. roy Soc. Lond., (A) *110:* 738–752.
Oxner, Mieczyslaw
1920. Chloruration par la méthode de Knudsen. Bull. Comm. int. Explor. Méditerr., No. 3: 1–36.
Schaefer, V. J.
1946. The preparation and use of water sensitive coatings for sampling cloud particles. Gen. Elec. Res. Lab. Rep., A. T. S. C. Contract W-33-038-AC-9151. pp. 1–17.
1949. Personal communication.
Sheppard, P. A.
1947. The constitution of clouds and the formation of rain. Sci. Progr., *35:* 490–505.
Simpson, G. C.
1941. On the formation of cloud and rain. Quart. J. R. met. Soc., *67:* 99–134.
Spilhaus, A. F.
1943. Atmospheric pressure, temperature and humidity, the corrections for aircraft speed. (Unpublished)
Sverdrup, H. U., M. W. Johnson and R. H. Fleming
1942. The Oceans. Prentice-Hall, Inc., New York. 1087 pp.
Wright, H. L.
1940a. Sea-salt nuclei. Quart. J. R. met. Soc., *66:* 3–12.
1940b. Atmospheric opacity at Valentia. Quart. J. R. met. Soc., *66:* 66–77.

Contribution No. 459

THE FIELD USE OF A SALINITY-TEMPERATURE-DEPTH RECORDER[1]

By

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INTRODUCTION

A salinity-temperature-depth recorder that provides a continuous record of the salinity and temperature of sea water has been described by Jacobson.[2] The present paper is a discussion of the use of this instrument in the field and of its application to a variety of hydrographic problems.[3]

The instrument consists of a measuring unit connected to a computing and recording assembly by an appropriate length of multiple-lead cable. The measuring unit, shown in Fig. 1, responds to the temperature and conductivity of the sea water and to the pressure (depth) at which these variables are being measured. In the computing and recording assembly, shown in Fig. 2, the salinity is automatically computed from the conductivity and temperature signals and is recorded together with the temperature and the depth on a moving chart. The instrument operates on a 110-volt 60-cycle current. The salinity is determined over the range 20 to 40 °/₀₀, generally with an error not exceeding ±0.25 °/₀₀, and the temperatures from 28° to 90° F. are recorded with a limit of error of about ±0.2° F.

Several instruments have been built. The first was an experimen-

[1] Contribution No. 459 from the Woods Hole Oceanographic Institution. This paper is based in part on research conducted under contract with the Bureau of Ships, Navy Department, which has given its permission for publication. The instrument was developed by the Bristol Company under subcontract with the Woods Hole Oceanographic Institution.

[2] Jacobson, A. W. An instrument for recording continuously the salinity, temperature, and depth of sea water. Trans. (mon.) Amer. Inst. elect. Engrs., Vol. 67: 714–722, August 1948.

[3] The author wishes to acknowledge the contributions of the many persons who have been associated with this work, particularly Allyn C. Vine, who initiated its development, A. W. Jacobson and John L. Russell, both of the Bristol Company, who designed and built the instrument, and A. C. Redfield, who has supervised the work since its inception. John Holmes and Otis Hunt have been responsible for shipboard installation and maintenance and Carlyle Hayes has assisted in much of the field work.

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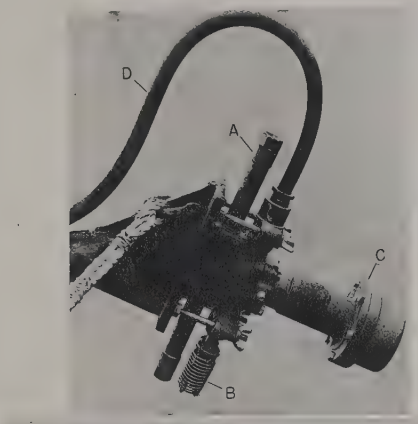

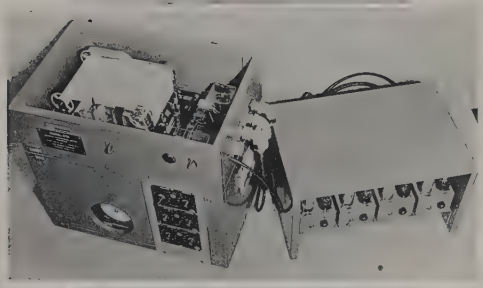

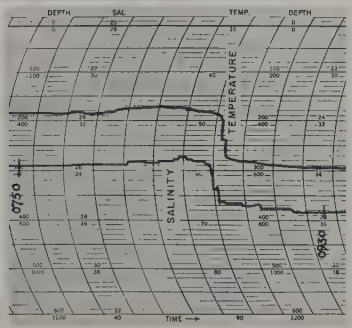

Figure 1 (top). Measuring unit mounted on outboard support. A, conductivity cell; B, resistance thermometer; C, depth element; D, cable. Figure 2 (middle). Recording unit, showing computer and strip chart at left, amplifier assembly at right. The dial in side of computer indicates conductance. Figure 3 (bottom). Record made while crossing northern boundary of Gulf Stream, April 24, 1947. Position at time 0750, 39°26' N, 69°55' W; at time 0930, 39°16' N, 69°52' W. Measuring element at 3.5 feet depth. Salinity scale 28-40 °/oo.

tal assembly which did not include a depth recording mechanism. Later models record depth and embody certain other improvements. Three of the instruments have each had several hundred hours of operation at sea.

For reasons of brevity and in view of the limited number of the models of the instrument, details on installation, testing and calibration are omitted. Such information may be obtained from either the Woods Hole Oceanographic Institution or the author.

APPLICATIONS

Field use of the instrument falls into two categories: (1) the determination of the horizontal distribution of salinity and temperature near the surface by continuous measurement from a moving vessel and (2) investigations of the vertical distribution of these variables during which the vessel must be hove to. In either case the instrument has proved useful, since it gives a continuous record of the variables and because the observer is immediately informed of existing conditions, thus permitting the survey program to be adapted to best advantage at the time.

For surface studies three methods have been employed: (1) a continuous record is made during a voyage which reveals critical conditions along the course; (2) the ship is sailed on a grid to give adequate coverage to an area; and (3) a particular band of isohalines is followed by a zigzag course which repeatedly crosses them. To obtain such records of salinity and temperature the measuring unit is usually mounted on a support extending from the deck of the vessel into the water.

For vertical measurements two methods have been used. In shallow, sheltered waters with sharp gradients, the measuring unit is lowered stepwise on a measured cable and provision is made for flushing of the conductivity cell by a pump. In deeper water the depth recording mechanism is employed and the measuring unit is lowered continuously. This is conveniently done by the use of a gypsy-head winch. Examples of these methods are discussed below.

1. *The Recording of Critical Changes of Salinity and Temperature During a Voyage.* During a voyage which may be conducted for other purposes, information on surface conditions is conveniently obtained by operating the instrument continuously, thus providing records of critical changes in surface salinity and temperature. Such data have demonstrated, for example, that the boundaries of water masses are frequently remarkably sharp. Fig. 3 is a record made while crossing the northern edge of the Gulf Stream. In this case

the chart was moving at such a speed that one division corresponds to 2,700 yards traversed by the ship. Thus it may be seen that the transition from slope water to Gulf Stream water took place in about 500 yards, during which salinity increased by 1.6 °/₀₀ and the temperature by 9° F.

2. *The Determination of Surface Distribution of Salinity and Temperature by Operating on a Grid.* Studies of the distribution of surface salinity and temperature in an area are made by travelling back and forth on a grid with the instrument giving a continuous record of the salinity and temperature. Two examples of this technique follow:

The surface distribution of salinity in Mount Hope Bay, obtained during the ebb tide, is shown in Fig. 4. The course taken by the vessel is indicated by the fine straight lines. In two hours a rectangular area measuring roughly 1½ x 2½ miles, or 6¾ square miles, was covered.

The surface salinity distribution in an area off New York as it was found on 24 April 1948 is shown in Fig. 5. In this survey an area of 700 square miles was covered in 24 hours even though interrupted by other hydrographic operations.

3. *The Determination of Surface Distribution of Salinity by Following Isohalines.* Another method for examining the surface distribution of salinity is to trace a band of isohalines by a zigzag course. This method was used successfully in a study of the distribution of Merrimack River effluent in Ipswich Bay. The results, illustrated in Fig. 6, were obtained in a period of three hours.

The procedure followed in this study will be discussed in some detail, since the technique is generally applicable. Fig. 6A is a working plot (somewhat simplified) of the vessel's course and of the salinities as taken from the record. The plot was kept up-to-date during the course of the survey so that the developing pattern was known. It will be seen that the outer circuit appeared not to be closed. This was due to errors in dead-reckoning navigation which had to be relied upon for a part of the circuit. When corrections based on fixes and fathometer data subsequently available were applied, the finished pattern shown in Fig. 6B was constructed.

A portion of the actual trace, taken during this study, is given in Fig. 7, since it illustrates the type of record obtained in surface studies. It includes all of the inner circuit shown in Fig. 6. In order that the data on the trace may be translated into their geographical frame of reference, the record is marked with the time at which the vessel passes a known position or changes course or speed. It is

also valuable to note on the record such events as the lowering of a bathythermograph or of the crossing of rifts in the water.

4. *Vertical Measurements of Salinity and Temperature.* The usual procedure of obtaining vertical measurements of salinity and temperature is to lower the measuring unit supported by its own cable

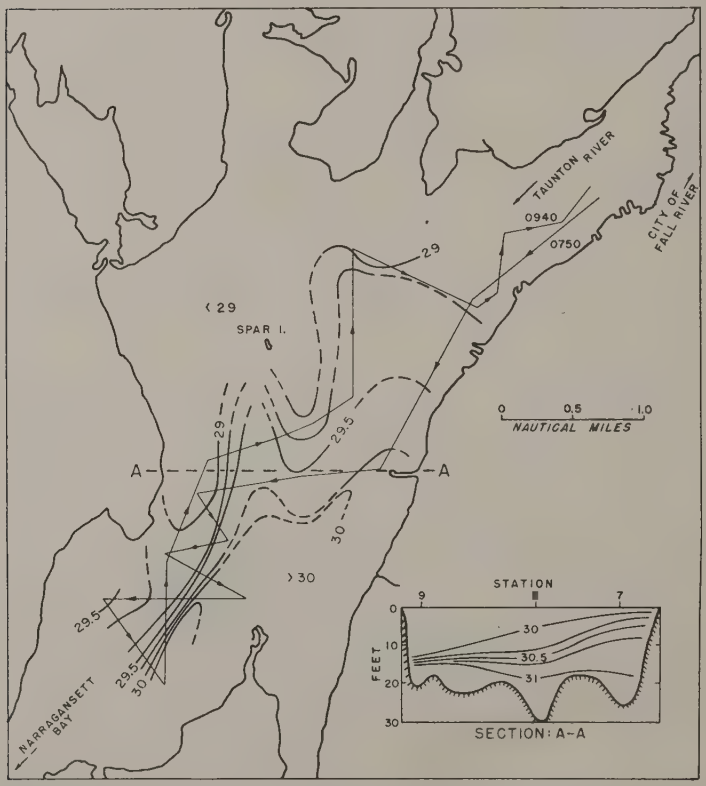

Figure 4. Distribution of salinity in surface waters of Mount Hope Bay. The light solid line shows course of vessel. Measuring element at 2.0 feet depth. November 10, 1944. Time 0750 to 0950.

Inset—Vertical section along A–A showing distribution of salinity in depth during ebb tide. November 13, 1945.

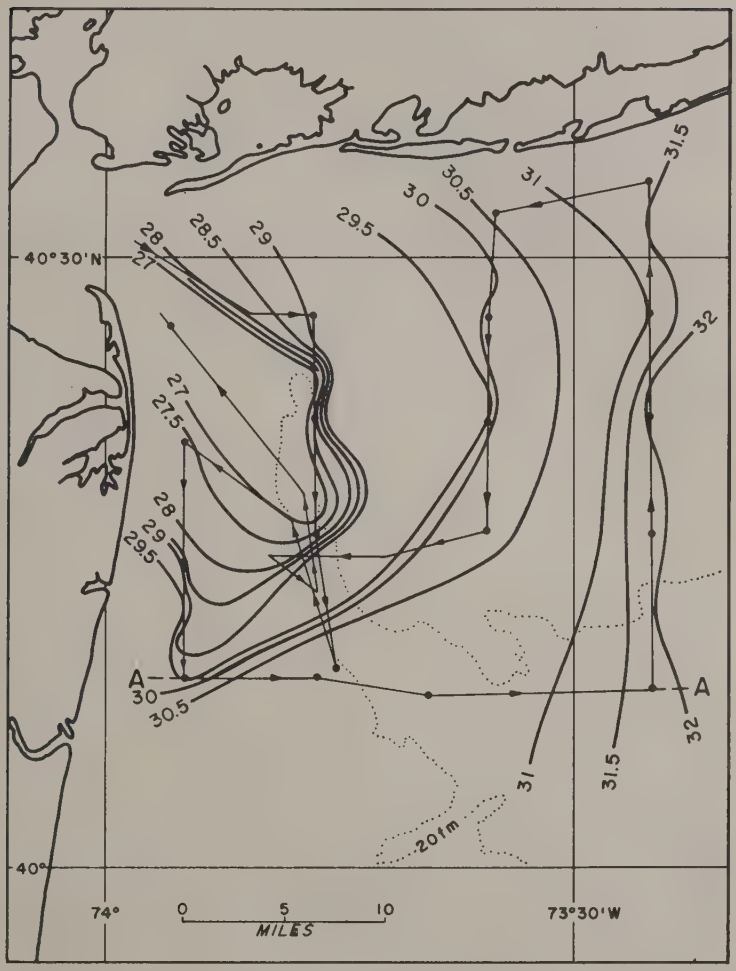

Figure 5. Distribution of salinity in surface waters off New York, April 24–25, 1948. Course of vessel shown by light line; isohalines by dark lines.

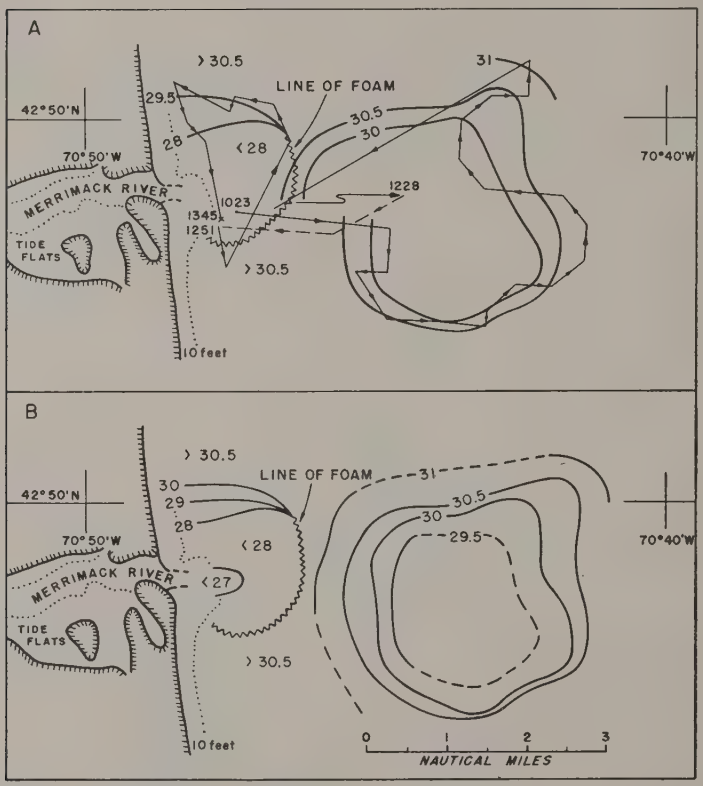

Figure 6. A. Working plot of distribution of isohalines at mouth of Merrimack River. The light line represents vessel's course by dead reckoning; the heavy lines show observed distribution of isohalines, the zigzag line shows position of foam at convergence of estuarine waters with the coastal water. September 7, 1946; time 1023 to 1345. High water was at 0934. Measuring element at 3 feet.

B. Reconstruction of distribution of salinity at mouth of Merrimack River after correcting for errors in dead reckoning. September 7, 1946.

while the vessel is hove to. If lowered at a rate of two to three feet per second, adequate flushing of the conductivity cell is ordinarily obtained. An example of the chart record that is obtained is given

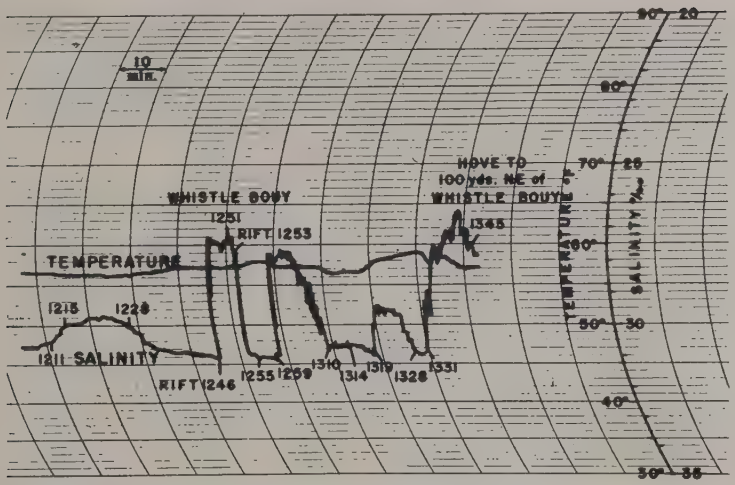

Figure 7. Record made during study of distribution of isohalines at mouth of Merrimack River, shown in Fig. 6. September 7, 1946; time 1200 to 1345.

in Fig. 8. On this occasion the lowering was completed in four minutes.

The jagged character of the depth trace is the result of the stepwise action of the depth-measuring mechanism, the unevenness of lowering by hand and of the roll of the vessel. The use of a gypsy-head winch improves the character of the depth trace.

Jogs appear in the salinity trace when abrupt temperature changes are encountered. One of these is identified at point A in Fig. 8 and corresponds to the temperature change at point B. Jogs originate in the fact that the automatic computation of salinity from temperature and conductivity assumes simultaneous measurement of these two variables, whereas in practice there is a tendency for the measurement of temperature to lag at points of abrupt change, hence introducing an error in salinity.

In Fig. 8 the arcs traversed by the three pens of the recorder are indicated as A, B and C. To read the record a transparent template, ruled with these arcs, is used.

To illustrate the accuracy that may be expected from the trace during a vertical lowering, the temperature and salinity from the record referred to above have been plotted as a function of depth in Fig. 9. Both the downward and upward traces are plotted to show the

combined effects of thermal lag in the resistance thermometer, "flushing" lag in the conductivity cell and sensitivity of the depth element. The latter has an error of about four feet. The combined effects, in this lowering, introduced an uncertainty of six to seven feet in the depth of the maximum gradient. The salinities, obtained by analysis of the

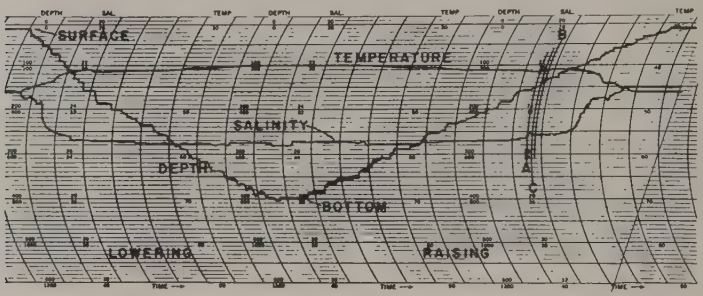

Figure 8. Record made during study of distribution of salinity and temperature with depth, off New York. Depth scale marked 100/200 equals 50 feet. Salinity scale 28–40 °/₀₀ in use.

Nansen bottle water sample using the Knudsen method, and the temperatures, as obtained from the reversing thermometers, have also been plotted in Fig. 9. The agreement with the recorded data is indicative of what can be expected of the instrument in routine operation.

In the course of determining the distribution of salinity off New York, lowerings were made on a grid work of stations (see Fig. 5) to establish its vertical distribution. A section from this grid is shown in Fig. 10 to illustrate the application of the instrument to the determination of salinity profiles. Of course temperature profiles, which are not shown, are also obtainable from the record.

In sheltered estuarine waters the vertical gradients of salinity and temperature are often very sharp and close to the surface, thus requiring accurate measurement of depth and a special procedure for avoiding the lag encountered when the measuring unit passes through the gradient. Since the depth recording mechanism provided with the instrument is not sufficiently accurate, depth is determined by measuring the amount of cable out. Lag is avoided by lowering the measuring unit stepwise, stopping at each depth long enough for equilibrium to be attained. Under these circumstances provision

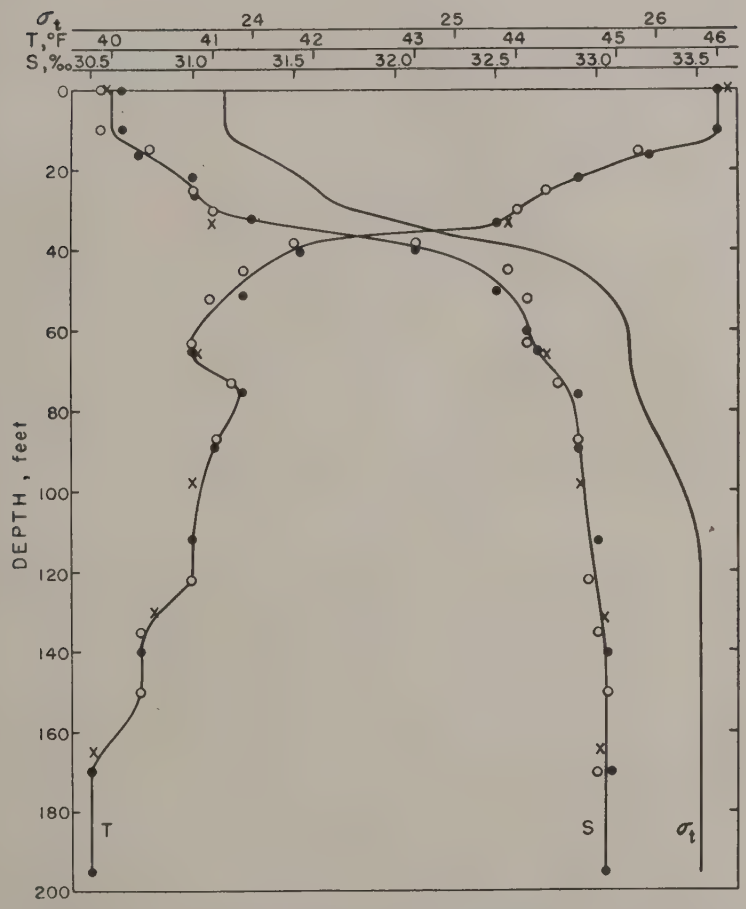

Figure 9. Plot of vertical distribution of salinity and temperature reconstructed from record shown in Fig. 8. The curves are drawn through points measured during lowering (dots) and raising (circles) of the measuring element after correcting for systematic errors of +0.5 ‰ in salinity and −0.2° F. in temperature. Crosses represent determinations made simultaneously by standard hydrographical procedures. The curve showing σ_t was obtained from the smoothed curves of temperature and salinity.

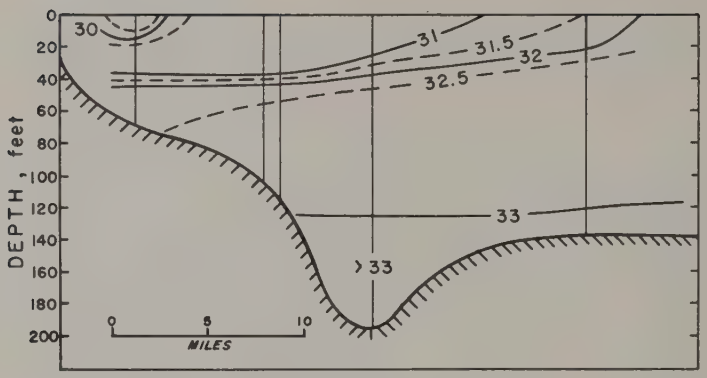

Figure 10. Vertical distribution of salinity along section A–A shown on Fig. 5 obtained by combining continuous observations of surface salinity and measurements made by lowering the measuring unit at the positions shown by light vertical lines.

must be made for flushing the conductivity cell. A small electric pump attached to the cell and powered through a cable from the vessel has proved satisfactory for this purpose. An example of results obtained by this procedure is given in the inset of Fig. 4.

Calibration. A constant check on the calibration must be maintained since it may vary with time. Therefore, water samples are taken at intervals during a survey and their salinity determined by the Knudsen method. The temperature is also checked with a suitable thermometer.

There are two types of error in the recording of both salinity and temperature, the systematic and inherent. Typical values of these errors, as determined during field operations, are given in Table I together with a definition of the terms. The systematic error is a function of the proper adjustment of the pen arm, various resistors in the circuit and the variable capacitors. Ideally, these may be adjusted to reduce the systematic error to zero, but in practice this is not feasible. The inherent error is the real uncertainty in the instrument's ability to measure the variable in question. It is a function of the temperature, salinity and design of the instrument.

TABLE I.—Examples of Systematic and Inherent Errors (in °/₀₀)

Cruise	S_0	S	a	k
Asterias	30.88	31.22	+0.34	+.21
7 Sept., 1946	30.91	31.20	+.29	+.16
	31.06	31.10	+.04	−.09
Temperature	31.13	31.35	+.22	+.09
53–55° F.	31.22	31.45	+.23	+.10
	31.16	31.27	+.13	.00
Recorder No. 0	31.00	30.95	−.05	−.18
	31.02	31.25	+.23	+.10
	31.08	31.23	+.15	+.02
	30.51	30.85	+.34	+.21
	30.95	30.80	−.15	−.27
	31.17	31.10	−.07	−.20
	31.14	31.25	+.11	−.02
	30.98	31.00	−.02	−.15
	30.90	31.00	+.10	−.03
	30.86	31.05	+.19	+.06
			$\bar{a}$ = +0.13	$\bar{k}$ = 0

Standard deviation = ±0.13
Spread = +0.21 to −0.27

Cruise	*Temp.*	S_0	S	a	k
Balanus B 9	47.0° F	32.68	32.20	−0.48	0.00
	56.7	34.45	33.97	−.48	.00
19–23 May, 1947	69.3	36.00	35.55	−.45	+.03
	75.5	36.07	35.75	−.32	+.16
Woods Hole to	77.0	36.18	35.65	−.53	−.05
Gulf Stream and	63.5	35.62	35.05	−.57	−.09
return	54.5	33.55	33.08	−.47	+.01
	50.0	32.92	32.25	−.67	−.19
Recorder No. 2	51.0	32.29	31.90	−.39	+.09
	54.0	31.85	31.40	−.45	+.03
				$\bar{a}$ = −0.48	$\bar{k}$ = 0.0

Standard deviation = ±0.10
Spread = +0.16 to −0.19

Note: S_0 = salinity by chemical analysis.
S = salinity by recorder.
a = S − S_0.
$\bar{a}$ = systematic error.
k = a − $\bar{a}$ = inherent error.

SUMMARY

Applications and operating characteristics of the salinity-temperature-depth recorder are demonstrated by illustrations taken from studies made on the effluent of the Merrimack River in Ipswich Bay, on the Taunton River-Mount Hope Bay estuary, on the waters off New York Harbor and on the Gulf Stream.

Contribution No. 460

Reprinted from SCIENCE, February 11, 1949, Vol. 109, No. 2824, pages 143–144.

Underwater Listening to the White Porpoise (*Delphinapterus leucas*)

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Recent developments in underwater acoustics have led to considerable speculation on the sounds made by cetaceans. Exclusive of those incidental to breathing or splashing at the sea surface, there is a variety of sounds which several species are known to make habitually while submerged. Published accounts allude to such sounds as heard through the air, but there seems to be no record of what can be heard by listening in the whales' own medium.

To learn more of the extent to which particular cetaceans do make underwater noises and how they sound under natural conditions on underwater listening apparatus, we wished to find an area where a single species was plentiful enough to be observed and listened to for relatively long periods. The white whale or porpoise, *Delphinapterus leucas* (Pallas), suggestively nicknamed "sea canary" (*1, 2*), seemed a promising subject and was known to occur in large numbers in the St. Lawrence estuary. As suggested by Vladykov's recent comprehensive works (*10, 11*) on this species, we found a good concentration in the lower Saguenay River in Quebec. The white porpoises were remarkably numerous, passing up and down the river in groups of various sizes throughout the day, so that we were able to listen to them for hours at a time, while watching them through field binoculars. Furthermore, no other cetaceans were observed there, although the little piked whale, *Balaenoptera acutorostrata* Lacépède, was seen in the St. Lawrence River a few miles away.

Our listening gear (a conventional underwater microphone, or hydrophone, with an amplifier) enabled us to hear over a frequency band between somewhat less than 500 and 10,000 cycles/sec, well within the normal human audible range. Strong currents, shoals, tide rips, and traffic in the St. Lawrence contributed to a noise background sufficiently high to interfere with our hearing. In the lower Saguenay the deep water (over 100 fathoms) and our good fortune in having little wind gave us the quiet essential for good listening, although there were two intervals with strong gusts of wind when the waves drowned out the sounds made by *Delphinapterus* nearby.

We found the water remarkably free of animal noise except when *Delphinapterus* were within range. Whenever we saw them we heard a variety of sounds which would become louder as the porpoises were seen coming around a bend in the river and would die away as they passed out of sight. But for the two occasions of rough water, we never sighted them without hearing them, and rarely heard them without seeing them, except after dark.

The noises which we thus ascribed to *Delphinapterus* were heard as high-pitched resonant whistles and squeals, varied with ticking and clucking sounds slightly reminiscent of a string orchestra tuning up, as well as mewing and occasional chirps. Some of the sounds were bell-like, and a few rather resembled an echo sounder. Occasionally the calls would suggest a crowd of children shouting in the distance. At times there were sharp reports, somewhat like a blow with a split bat or a slap on the water, although nothing could be seen to be striking the water in any way; perhaps this was jaw snapping, as reported for *Tursiops* by McBride (*3*, p. 25; *9*, p. 112). On two occasions we heard trilling, which quite justified the name "sea canary." This description is given with some diffidence in view of the notorious difficulty of adequately describing unfamiliar sounds. We hope to make phonographic recordings at another opportunity.

It is to be emphasized that all these sounds were made under water. We heard them only through the hydrophone, which was at depths of 60 to 90 feet; the porpoises were never nearer than about 200 yards, and often over two miles away. Mostly they passed along the far side of the river in their usual series of short dives (5–10 seconds' submergence, perhaps 50 feet of horizontal progression), but sometimes they would make unusually long dives (up to about half a mile) apparently to avoid us; in either case their calls continued uninterrupted. Axel Olsen and Léopold Boulianne, of Tadoussac, Province of Quebec, who accompanied us, said that they had previously heard whistles when *Delphinapterus* passed directly beneath their canoe, but that they had never heard such a variety of sounds as they now did over the underwater gear. Similarly, the underwater sounds heard by earlier authors (Fisher, *3, 4*; Kane, *6*; Nielsen, *8*; and others, summarized by Vladykov, *10*, pp. 121–124) may be recognized among the list of those we heard, although no single listener seems to have heard them all, perhaps because they were handicapped by listening through the air instead of through the water alone.

[1] Contribution No. 460 from the Woods Hole Oceanographic Institution.

[2] The authors are indebted to officials of the Province of Quebec, especially to Dr. Vadim-D. Vladykov, of the Department of Marine Fisheries, for cordial advice and assistance, to Mr. Charles Frémont, General Superintendent of Game and Fisheries, and to Dr. Robert Lagueux for his hospitality at the Tadoussac Fish Hatchery.

Since fish noises predominate in other regions, it seems strange that none were identified here, except for those caused by their biting and pulling at the hydrophone. It is possible that some of the sounds might be of fish origin, but it is significant that only the bites were detected in the absence of *Delphinapterus*.

Particularly striking is the great variety of *Delphinapterus* sounds and their rapid and apparently continuous succession. This loquaciousness contrasts markedly with most terrestrial herd mammals and compares with such chatterboxes as monkeys and men. Among the Cetacea it would appear not to be limited to *Delphinapterus*, as is indicated by the continuity of related but less varied sounds heard by one of us in the presence of different porpoises in the open Atlantic, as well as those on phonograph records at the Woods Hole Oceanographic Institution which are believed to be of porpoises. The considerable difference between the sounds we heard in the presence of *Delphinapterus* and the less spectacular ones associated with *Delphinus* (Kullenberg, *7*; Fraser, *5*), *Tursiops* (McBride, *8*, p. 19; *9*, pp. 112–113), and other pelagic forms encourages us to hope that these underwater calls may be sufficiently characteristic to be helpful in distinguishing cetaceans at sea. Such listening probably will have to be carried into the supersonic range.

Only toothed whales (Odontoceti) have figured in the reports so far encountered. It would be of interest to learn of any authenticated instances of hearing underwater sounds from baleen whales. Among these, our experience with listening apparatus is limited to the solitary individuals of *Balaenoptera acuto-rostrata* mentioned earlier; we distinguished no underwater sounds even when a whale was within 300 yards.

References

1. Beddard, F. E. *A book of whales.* New York: G. P. Putnam's Sons; London: John Murray, 1900. P. 245.
2. Degerböl, M., and Nielsen, N. L. *Meddelelser om Grönland,* 1930, **77**, 140.
3. Fisher, Alexander. *A journal of a voyage of discovery to the Arctic regions in H. M. S. Hecla and Griper in the years 1819 & 1820.* (2nd ed.) London: Printed for Longman, Hurst, Rees, Orme, and Brown, 1821. P. 73.
4. Fisher, Alexander. *In* W. E. Parry. *Journal of a voyage for the discovery of a north-west passage from the Atlantic to the Pacific . . . H.M.S. Hecla and Griper. . . .* London: John Murray, Publisher to The Admiralty, and Board of Longitude, 1821. P. 35.
5. Fraser, F. C. *Nature, Lond.,* 1947, **160**, 759.
6. Kane, Elisha Kent. *The U. S. Grinnell Expedition in search of Sir John Franklin.* New York, 1854. P. 359.
7. Kullenberg, B. *Nature, Lond.,* 1947, **160**, 648.
8. McBride, A. F. *Nat. Hist.,* 1940, **45**, 16–29.
9. McBride, A. F., and Hebb, D. O. *J. comp. physiol. Psychol.,* 1948, **41**, 111–123.
10. Vladykov, V.-D. Chasse, biologie et valeur économique du marsouin blanc ou béluga (*Delphinapterus leucas*) du fleuve et du golfe Saint-Laurent. (Etudes sur les mammifères aquatiques, 3.) Quebec: Département des Pêcheries, 1944.
11. Vladykov, V.-D. Nourriture du marsouin blanc ou béluga (*Delphinapterus leucas*) du fleuve Saint-Laurent. (Etudes sur les mammifères aquatiques, 4.) Quebec: Département des Pêcheries, 1946.

Contribution No. 461

Reprinted from SCIENCE, March 18, 1949, Vol. 109, No. 2829, pages 271–274.

A New Development in Ocean Wave Research[1]

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APPLICATION OF THE PRINCIPLES of generalized harmonic analysis to oceanic wave observations is here briefly reported. This type of analysis is new to oceanography and has rarely been used in other geophysical practices (*2, 3*). In our case it was applied initially to observed oceanic wave data as a means of overcoming ambiguities and uncertainties arising from the fitting of Fourier series and from apparent misleading indications of periods from periodogram analyses of finite amounts of data.

The hypothesis of generalized harmonic analysis provides a realistic approach to the subject of oceanic wave investigations. As will be shown, the outcome of the applications far exceeded initial expectations. The results obtained identify the method as a powerful tool for this type of investigation and, provided the hypothesis is applicable to the problem, it serves two distinct purposes:

(1) To separate the dynamic and random components of oceanic wave patterns, and to evaluate the physical characteristics of each.

(2) To employ the above results in investigations of the corresponding properties of the physical generating mechanisms.

The dynamic components of ocean wave patterns are presumed to be those generated by systematic action of winds on the sea surface. On the other hand, random components result from variables not considered, such as random motions of the water and local intermittent wind action. Separation of dynamic and random effects in this sense is paralleled in electrical communication, wherein the initial signal frequency is distorted to a varying degree, and distortion of a purely random nature is called noise. On arrival, a message contains the original signal frequency plus a random noise, and the problem is to isolate the initial signal from the message. The analogy to be drawn for ocean waves is that the ocean wave record is comparable to the message, the dynamic portion of the record to the signal, and the superimposed randomness to the noise.

The oceanic wave observations subjected to analyses were obtained in the usual manner, by photographic recordings of sea surface wave heights and by automatic recordings of wave pressure variations at the sea bottom (*1*). Such observations comprise geophysical time series from which discrete values of wave heights are scaled at equidistant (1 second) time intervals. Sequences of values so obtained contain certain inherent dynamic properties, together with certain superimposed random components.

Separation of the dynamic and random components and evaluation of their cyclical and oscillatory characteristics are possible by the hypothesis of generalized harmonic analysis. In this manner we eliminate the objectionable a priori assumptions of Fourier series applications to geophysical time series, and obtain results of dynamic significance. Thus, application of the Fourier series to a finite stationary time series permits representation by an infinite number of sums of sine waves of different periods and amplitudes, whereas the correlogram of generalized harmonic analysis is, like the original series, the sum of a series of harmonics with different coefficients, all in phase. The correlogram brings to light a more realistic and more simplified picture of the physical characteristics of the sea surface pattern. The nature of this information is briefly discussed in connection with an analysis of Wave Record 53-X.

A detailed report by the authors on the method of generalized harmonic analysis, together with a rigorous mathematical treatment of the specific applications and representative examples, will be published shortly. Essentially, the method consists of analyzing the correlogram of auto and cross correlations of the data. Thus, as an example, in the series

$$u(t) = A_1 \sin(\lambda_1 t + \alpha_1) + A_2 \sin(\lambda_2 t + \alpha_2) + \ldots\ldots\ldots\ldots A_m \sin(\lambda_m t + \alpha_m),$$

the variance is

$$\operatorname{Lim} \frac{1}{2h} \int_{-h}^{h} u^2(t)\,dt = \tfrac{1}{2} \Sigma (A_j^2),$$

and the auto correlation function is

$$r(k) = \frac{\Sigma\{A_j^2 \cos(\lambda_j k)\}}{\Sigma\{H_j^2\}}.$$

Record 53-X (Fig. 1) designates a 20-min underwater (70′ depth) pressure record from a location one and one quarter miles south of Cuttyhunk Island, Massachusetts, beginning at 0650, September 15, 1946.

[1] Contribution No. 461 from the Woods Hole Oceanographic Institution and the Department of Mathematics, Massachusetts Institute of Technology.

Previous periodogram analysis of this data, by means of the wave frequency analyzer in use at this Institution (*1*), produced the result illustrated in Fig. 2. The periodogram is a complicated picture with numerous periods. This represents the customary type of

Fig. 1. Portion of Wave Record 53-X. On the original record the upper 30-sec time marks are approximately 1¾" apart.

oceanic wave record analysis, and in the usual interpretation, two distinct frequency bands would be defined as characterizing the data. The first, not too well represented, lies between 6.5 and 8.00 seconds, and the second, well-defined, between 10.5 and 16.0 seconds. Maximum peaking occurs at 12.5 seconds, with two additional, well defined peaks at 11.5 and 15.0 seconds. Hence, the usual conclusions drawn from this analysis would be that the sea surface roughness pattern consists of two defined spectral bands with a dominating period in the vicinity of 12.5 seconds.

Although conclusions like these are not readily disproved, the accepted explanations of geophysical phe-

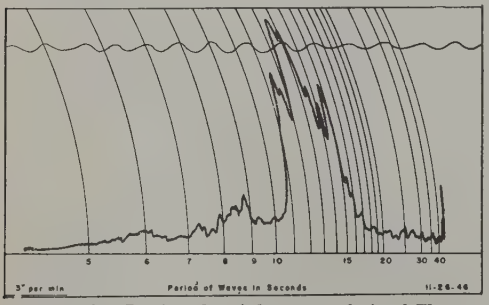

Fig. 2. Results of periodogram analysis of Wave Record 53-X, as given by the wave frequency analyzer.

nomena are those that provide the most realistic and simplified hypothesis. In this case, the fallacy in the analysis appears to lie in the fact that the large number of periods shown for consideration is misleading. The mere fact that the data can be mathematically represented in this fashion does not lend significance to any identical period or group of periods. The component periods are not identifiable, and the period bands which may be construed as constituting the oceanic wave pattern do not possess a realistic physical significance. Rather, this type of analysis suggests that the large number of periods in the periodogram may be indicative of some one disturbed period in the series. Thus, it can be demonstrated by a generalized harmonic analysis of the original record (53-X) that the wave pattern is not an interference pattern composed of the numerous periods of Fig. 2, but one that is apparently controlled by a single

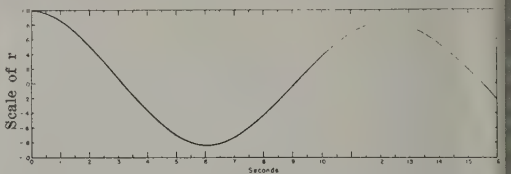

Fig. 3. Correlogram of Wave Record 53-X; 0- to 16-sec lags.

cyclical component on which is superimposed an oscillatory component of the same frequency. Combination of the two components results in the apparent complex basic wave pattern of the record (Fig. 1). This latter, and more realistic explanation, has been derived for Record 53-X in the following manner.

Correlograms of Wave Record 53-X for lag correlations of 0 to 16 seconds, 100 to 111 seconds, and 200 to 211 seconds are illustrated by Figs. 3 and 4. The sinusoidal symmetry of the curves and the time locations of valleys (6.13, 104.13, 202.13 seconds) and crests (12.25, 110.25, 208.25 seconds) indicate a persistent period very near to 12.25 seconds. The variance of the primary data is 0.1824 ft².

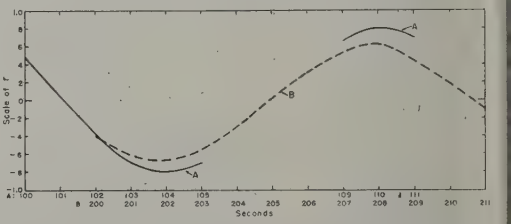

Fig. 4. Sections of correlogram of Wave Record 53-X for the 100- to 111-sec and 200- to 211-sec lags.

The correlogram damps slowly. At the 202nd lag the wave valley has an amplitude of $r_k = 0.66$, and near the 208th lag the crest amplitude is $r_k = 0.62$. The slight asymmetry appears to result from small errors in estimation of the mean value. The mean amplitude for the 16th cycle is taken as $r_k = 0.64$.

In the case where the series consists of a sine term, A sin θt, plus a random residual, we have as a theoretical value of the terminal amplitude of the correlogram

$$r_k = \frac{\text{variance cosine}}{\text{total variance}} = \frac{A^2 \cos \theta k}{2\sigma_y^2}.$$

Thus,

$$A = \sqrt{2}\,\sqrt{r_k}\,\sigma_y.$$

If the value of $r_k = 0.64$ and that for the variance of the primary data (0.1824 ft²) is substituted, the theoretical amplitude (A) of the 12.25-second cyclical component in Wave Record 53-X is computed to be: A = 0.49 ft.

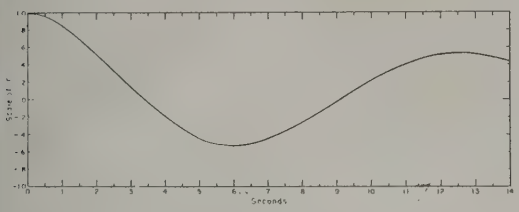

FIG. 5. Correlogram of residuals of Wave Record 53-X; 0- to 14-sec lags.

This value is in close agreement with the amplitude of 0.54 ft computed for the 12.25-second cyclical component by a least-squares fit of Fourier series to the primary data of 53-X. Subtracting this cyclical component from the primary data and computing the autocorrelation functions of the residuals, we obtain the correlogram of Fig. 5. The correlogram damps rapidly to an amplitude of $r = 0.54$ at the end of the first cycle, and thereafter continues to damp. The variance of the residuals is 0.0636 ft².

Substituting above values in the relation

$$\frac{\text{variance of residuals}}{\text{variance of primary data}} = 1 - r_k$$

where r_k is the terminal amplitude of the primary correlogram, we obtain $r_k = 0.656$; a value in good agreement with that of $r_k = 0.64$ for the terminal amplitude of the correlogram of the primary data (Fig. 4).

We may now proceed on the basis that, after extraction of the cyclical component from a finite amount of primary data, the residuals represent the autoregressive part of the primary data. Hence, the total or primary data may be considered to consist of a cyclical component and an oscillatory component, the latter of which is autoregressive. The correlogram of the residuals has a period of 12.25 seconds, identical with that for the primary data. From the Fourier transform of the autocorrelation coefficient, the intensity (S^2) in the periodogram of the residual series is computed. Fig. 6 illustrates the results which show that the energy of this spectrum attains its maximum value ($S^2 = 7.2$) at about 12.25 seconds.

Further numerical computation provides items of verification interest. Thus, multiplying the residual variance by the maximum intensity of the periodogram (Fig. 6) we obtain A = 0.67 ft as the theoretical amplitude of the oscillatory component.

The total amplitude of the sea surface oscillation (C) may now be computed as the square root of the sum of the squares of the cyclical and oscillatory component amplitudes. Thus

$$c = \sqrt{(0.54)^2 + (0.67)^2} = 0.86 \text{ ft.}$$

The mean deviation of the primary data is 0.362 ft; that for the residuals, after subtraction of the cyclical component, is 0.194 ft. Thus, the ratios of mean deviation to standard deviation for each case is: primary data = 0.84 and residuals = 0.77; or the mean deviation is approximately $\sqrt{2/\pi}$ of the standard deviation, a relationship which holds approximately for unimodal curves approaching symmetry.

Application of the hypothesis of generalized harmonic analysis permits the following geophysical interpretation of Wave Record 53-X. The wave pattern represented consists of a well-developed cyclical component (12.25-second period) on which is superimposed an oscillatory component of the same period. The former, which accounts for approximately 64 percent of the sea surface roughness, proceeds through the data as the predictable component, that is, as long as the generating mechanism remains unchanged. The oscillatory component represents the autoregressive part of the data. The cyclical component is presumed to be generated by a prominent oceanic meteorological situation, and the superimposed oscillatory component from local winds and other local disturb-

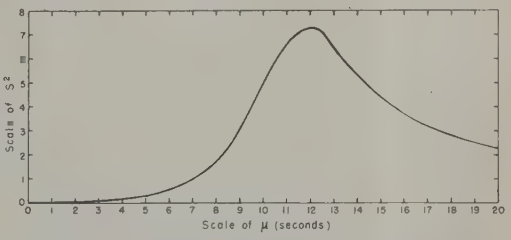

FIG. 6. Energy distribution (S^2) in periodogram of the residual services obtained from the Fourier transform of the autocorrelation coefficient.

ances which tend to change the basic wave pattern. The cyclical is the dynamic component, whereas the oscillatory component is random, although it may possess dynamic characteristics.

Most of the wave records[2] analyzed to date conform to the general pattern of Record 53-X; that is, a well developed cyclical component on which is superimposed an oscillatory component, plus, possibly, other random factors. In a few instances, the cyclical component has been absent, or so weakly developed as to be indistinct. In rare cases, two distinct cyclical components were evaluated from the primary data.

[2] These records comprise both sea surface and sea bottom observations. For observing methods see reference *1*.

The conclusions to be drawn from the foregoing analyses may be summarized briefly as follows:

(1) Periodogram analyses performed on oceanic wave records do not appear to give correct geophysical information. The numerous wave periods, and bands of periods, indicated by this type of analysis do not necessarily possess physical significance.

(2) Application of the hypothesis of generalized harmonic analyses to western North Atlantic wave records indicates that ocean wave patterns are not complex interference patterns resulting from combinations of many wave frequencies, but frequently consist of a single sinusoidal wave on which is superimposed an oscillatory component.

(3) The cyclical component appears to be that generated under the influence of a dominating oceanic meteorological situation, and the oscillatory component by local winds and other local disturbances tending to change the basic ocean wave pattern.

(4) Separation of the cyclical and oscillatory components and determination of their physical properties is possible by generalized harmonic analysis of finite portions of the primary data.

(5) In the case of Record 53-X, the wave pattern is indicated to be composed of a cyclical and an oscillatory component. The former proceeds throughout the data in regular sinusoidal fashion with an amplitude of 0.54 ft and accounts for approximately 64 percent of the variability in the wave pattern. The oscillatory component, with a theoretical amplitude of 0.67 ft is autoregressive, and strongly damped.

References

1. Seiwell, H. R. *Results of research on surface waves of the western North Atlantic.* (Pap. in Physical Oceanography and Meteorology.) 1948, **X**, 145, 4.
2. Wadsworth, George P. *Air Weather Service tech. Rep. 105–87.* Washington, D. C.: Air Weather Service. 1947.
3. Wiener, N. *The extrapolation, interpretation, and smoothing of stationary time series.* (NDRC Rep.) Cambridge, Mass.: NDRC, 1942.

Contribution No. 463

DISCUSSION OF SOME OF THE EFFECTS OF WINDS ON ICE DISTRIBUTION IN THE VICINITY OF THE GRAND BANKS AND THE LABRADOR SHELF

BY FLOYD M. SOULE AND E. R. CHALLENDER[1]

The movement of a floating object, such as a piece of ice, is controlled by the movements of the water surrounding the submerged portion of the object and the air surrounding the portion of the object which extends above the water line. The relative importance of winds and currents in contributing to the motion of the ice depends in large measure upon the shape of the piece of ice and the consequent proportion of the surface areas exposed to the two media. Thus the movement of a berg is usually controlled almost entirely by currents, whereas the movement of a field of sea ice is more affected by winds than by currents. Neither type of ice will be completely independent of either winds or currents. An established current system is the result of all of the factors which have been operating to produce forces tending to move or direct the motion of the water during a period of time in the immediate past. Probably the most important of these factors is the wind. The length of the period of time, immediately past, which needs to be considered as making significant wind-originated contributions to a current system is obscure. Winds prevailing for as much as a month have a pronounced effect on a current system. Winds associated with an individual storm lasting for about 2 days set up wind currents whose effects disappear with the passage of the storm. The effect of wind on floating ice is brought about by the direct action of the wind on the exposed part of the ice and by the indirect action of the wind on the submerged part of the ice through the alteration of the currents. The time factor becomes of greater importance when the draft of the ice is in the order of magnitude of 100 to 300 meters as it is in the case of bergs.

Because so little is known about the effect of wind on the drift of ice there are recorded here some data pertinent to the meteorological conditions which accompanied the unusual ice distribution observed during the 1947 season. Seemingly normal or abnormal amounts of both sea ice and bergs were in prospect for the 1947 season. The forecast, made by the use of the Smith[2] formulae, was for 550 bergs to drift south of latitude 48° N., compared with the 48-year average of 431 bergs. During the month of February the barometric pressure distribution was abnormal and along the Newfoundland-Labrador coast an unusually large proportion of onshore winds resulted. During February all of the field ice was destroyed and

[1] Contribution No. 463 of the Woods Hole Oceanographic Institution.

[2] Edward H. Smith, The Marion Expedition to Davis Strait and Baffin Bay, U. S. Coast Guard Bull. 19, part 3, 188 (1931), Washington.

most of the bergs in the area were driven close to the beach or disintegrated. Subsequently late-season ice did appear and bergs moved far enough south to endanger track C until 13 July. With these facts and circumstances it is of interest to examine the magnitude of the barometric pressure gradient in a direction parallel to the coast.

Daily synoptic charts, prepared by the aerological office of the Naval Air Station at Argentia, for 0630 G. g. t., were available for all but Sundays and holidays. Each chart was scaled as follows; selecting an area of rectangular shape with its length 600 nautical miles and its width 180 nautical miles and stretching along the Labrador-Newfoundland coast with its inshore long side running from 55° N., 57° W., to 46° N., 50° W., the barometric pressure gradients along each pair of parallel sides were averaged for each available chart, to get the gradient components which might be considered to apply to the area, centered at about 51° N., 51° W. Each component of the gradient (normal and parallel to the coast) was averaged for the month and the monthly averages resolved to get a resultant average gradient for each month from November 1946, through June 1947, inclusive. The long dimension of the rectangle selected is oriented at about 335½° and 155½° true. As the wind runs across the isobars at an angle of about 30° to the left at the surface in this region, and as the drift of floating sea ice (as a direct effect of the wind) is to the right of the wind by a variable amount approximating 45°, the ice drift has been taken as being directed 15° to the right of the geostrophic wind, the approximate value of which, expressed in knots, has been listed in the following table along with the average gradients of barometric pressure in millibars per nautical mile, and the resultant direction of the wind drift in degrees true estimated as described above.

Month	Direction of Wind Drift	Gradient	Wind
Nov. 1946	122	0.0131	9.9
Dec. 1946	128	0.0214	16.2
Jan. 1947	126	0.0250	18.9
Feb. 1947	304	0.0120	9.1
Mar. 1947	248	0.0080	6.0
Apr. 1947	130	0.0176	13.3
May 1947	080	0.0163	12.3
June 1947	113	0.0062	4.7

From this table it will be noted that the direction, which was constant during the months of November, December, and January, changed 180° between January and February and continued to have an onshore component during March, after which it returned to about its previous direction for the rest of the season. To clarify this picture, the drifts are shown in figure 13 in which the lengths of the vectors are shown as proportional to the gradients. The

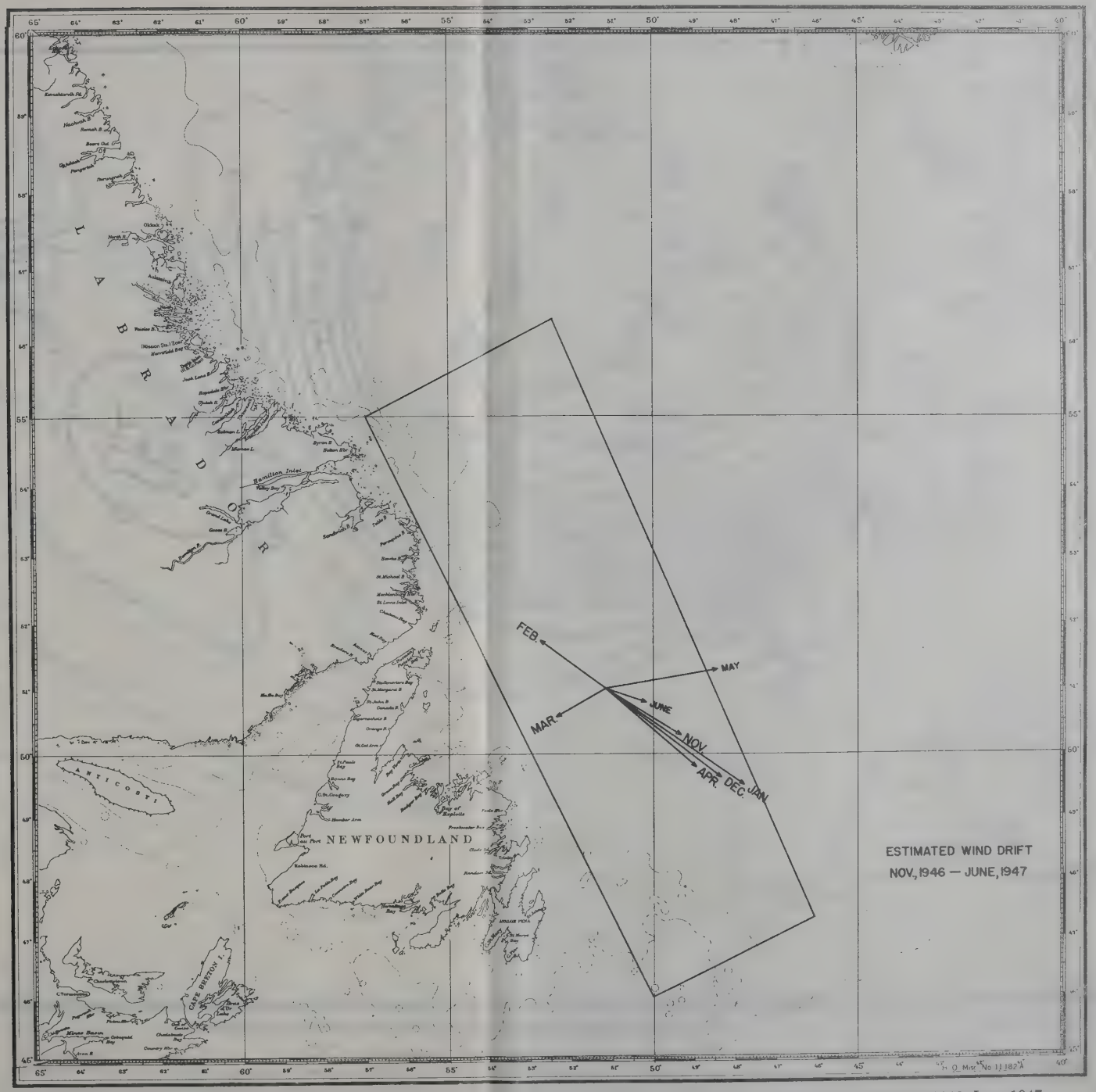

FIGURE 13.—Estimated wind drift of ice from monthly mean barometric pressure gradients in area indicated. November 1946–June 1947.

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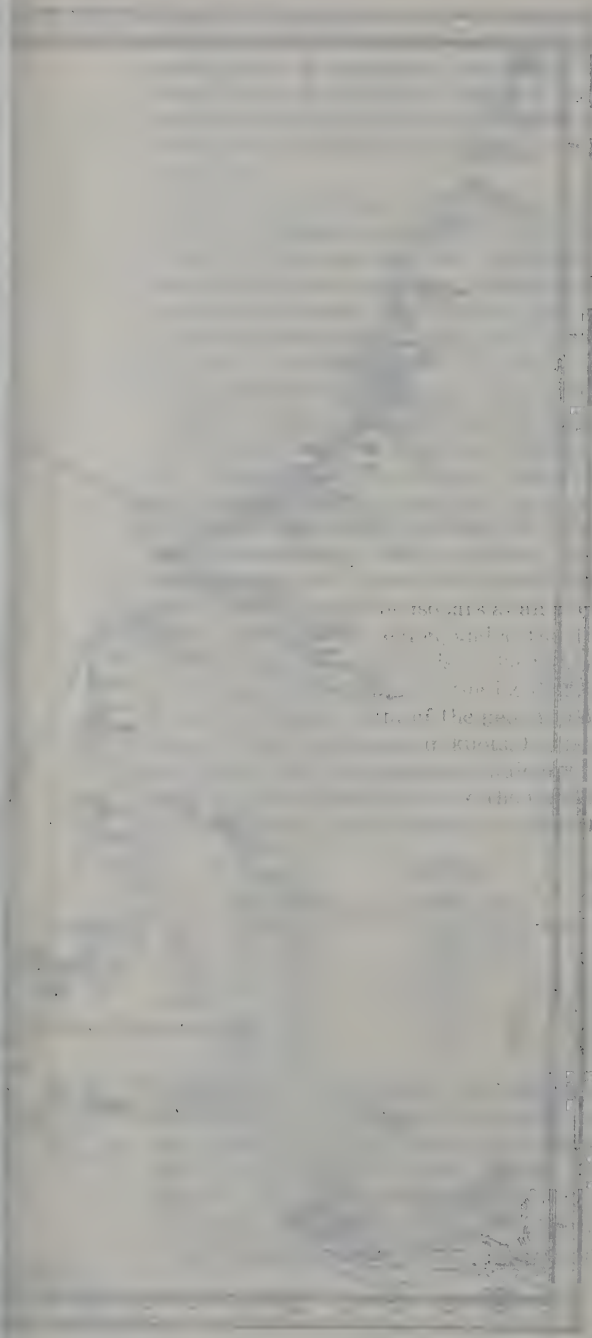

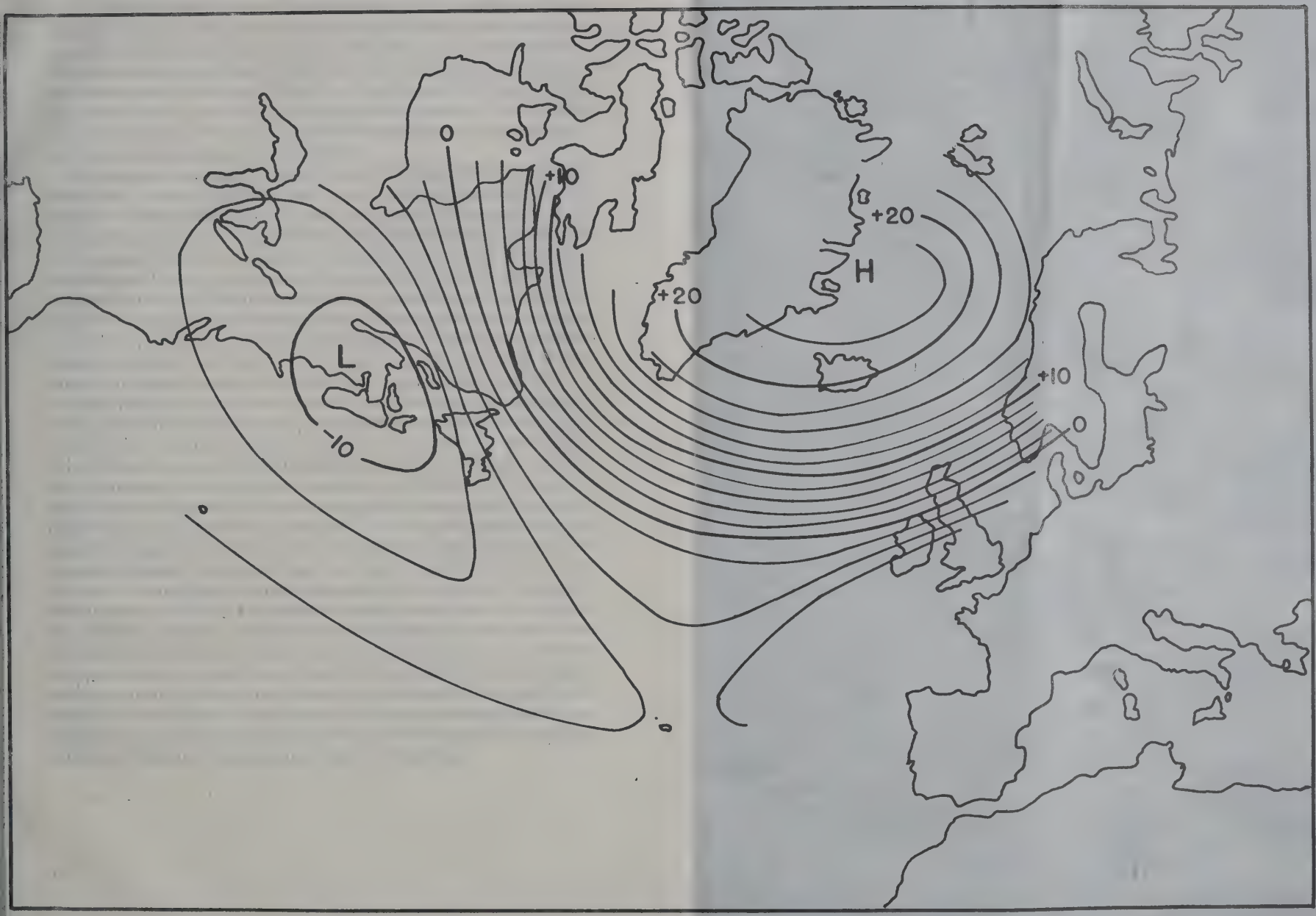

FIGURE 14.—Monthly mean barometric pressure anomaly, February 1947.

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normal barometric pressure distribution in February has a gradient approximately normal to the trend of the Labrador-Newfoundland coast with pressures decreasing offshore, and practically no gradient in a direction parallel to the coast, so that normally the February winds contribute to the Labrador Current and southeasterly movement of the ice. Figure 14 illustrates the extent of the departure from normal of the barometric pressure distribution during February 1947. The interval between lines of equal anomaly of barometric pressure is two millibars.

The onshore component of the winds in the Labrador-Newfoundland area during February, and to a smaller degree in March, resulted in the destruction of a major part of the ice crop which would otherwise have reached the Grand Banks region during the 1947 season. This is an aspect of the effect of barometric pressure distribution which is not taken into account in the Smith iceberg forecast formulae. The magnitude of the gradient producing such an effect is given in the foregoing table. The circumstances existing in 1947 are provocative of speculative inquiry. One question which arises is whether a strong offshore component of the wind, if sustained for several weeks, would not also result in the destruction of a year's berg crop since the water of the Labrador Sea northeastward of the continental slope is markedly warmer than is the water on the shelf. In answer, only a surmise is possible at the present time. The sea ice probably would be destroyed as effectively whether the component were directed onshore or offshore. However, the bergs driven aground by onshore winds are temporarily immobilized while their destruction proceeds. The immobilization not only impedes their southward travel but subjects them to greater mechanical stresses from heavy seas and therefore is likely to increase the rate at which they calve growlers and glacial debris. Because of the surface over which the onshore winds passed before arriving in the vicinity of the ice, higher probable air-temperatures lead to the expectation that the melting of the ice exposed to the air will proceed more rapidly than when the winds are offshore. One should expect that any onshore or offshore components in the winds will result in a reduction of the number of bergs reaching the Grand Banks region, and that the onshore winds will be more effective than offshore winds in bringing about such a reduction.

☆U. S. GOVERNMENT PRINTING OFFICE: 1949 O - 853338

Contribution No. 466

EXPERIMENTS IN THE FERTILIZATION OF A SALT WATER POND[1]

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It has long been recognized that the biological productivity of the sea depends primarily upon the nutrition of the phytoplankton. The aim of these experiments was to study this basic process in the cycle of production by the artificial increase of those plant nutrients most likely to become limiting. For our purpose a body of water was required which was large enough to be representative without excessive water exchange due to tidal action, yet small enough to permit an adequately conclusive study. Having selected a salt pond which met these requirements, the specific objectives were 1) to determine whether it is feasible to raise and maintain at high levels the concentrations of phosphate and nitrate by the addition of commercial fertilizers, and 2) to observe the effects of such increases upon the standing crop of phytoplankton.

A considerable body of evidence from laboratory culture work (e. g., Riley, 1943) and from fresh-water fish-pond management (e. g., Swingle and Smith, 1938) indicates that the concentrations of several nutrient salts may limit phytoplankton production simultaneously. For this reason frequently the maximal growth cannot be produced by supplying only one or two of the deficient elements. However, since our primary concern was to study the effects of different nutrients rather than to increase plankton production, we have confined our experiments to two substances, namely phosphate and nitrate, whose concentrations in the sea are limiting.

Compared with the work in fresh waters, fertilization of salt water areas has been rarely attempted. Evermann (1904), Gaarder (1932), Gaarder and Spärck (1932), and Gaarder and Alvsaker (1941) have fertilized partially enclosed bodies of salt water to increase the production of oysters. Frequent reference will be made to the work of Gross, *et al.*, who have improved the production of flatfishes in semi-enclosed sea lochs in Scotland (Gross, 1947; Orr, 1947; Marshall, 1947).

[1] Contribution No. 466 from the Woods Hole Oceanographic Institution.

Reprint from SEARS FOUND JOURN. MAR. RES

Edmondson and Edmondson (1947) discuss salt water fertilization experiments conducted in concrete tanks and in a natural pond.

The work of the Edmondsons and the present study form parts of a general study of productivity in marine waters, under the direction of George L. Clarke. Most of the plankton counts were made by Miss Mary Goffin and Theodore R. Rice. I am also indebted to George A. Bartholomew and Thomas F. Dolan for assistance in various chemical determinations.

METHODS

The water samples for all determinations were generally collected between 9 a. m. and noon, from a depth of a few inches below the surface.

Salinity was calculated from density measured with a special hydrometer.

Hydrogen-ion concentration was determined with a Hellige comparator and corrected for salt error (Wattenberg, 1937).

Inorganic phosphate concentration, determined by the modified Deniges-Atkins method (Wattenberg, 1937), was measured in a Klett-Summerson photoelectric colorimeter. Factors were applied for correction of salt error as determined by calibration. Concentrations are expressed as microgram-atoms of phosphate phosphorus per liter (μg.-at. PO_4 P/l.).

"Nitrate" was measured by Zwicker and Robinson's (1944) method, which does not distinguish between nitrate and nitrite. The measurements were made with a Klett-Summerson photoelectric colorimeter, using either filter no. 42 or no. 54. Concentrations are expressed as microgram-atoms of nitrate nitrogen per liter (μg.-at. NO_3 N/l.). For lack of the necessary strychnidine reagent, nitrate was not measured until late June 1947.

Zwicker and Robinson warn that inorganic reducing agents or high concentrations of plankton or of dissolved organic matter may inhibit color development in this test. The observed or probable presence of all three of these factors in the pond may explain the consistently low readings of nitrate which were obtained except during fertilization experiments. Due to these possible sources of error and to the fact that high blanks frequently necessitated the application of large correction factors, no great reliance should be placed on the absolute values obtained.

Phytoplankton. For the quantitative analysis of the phytoplankton, two different procedures were employed. In 1946 water samples were preserved with 3% formalin, the plankton counted after settling and

centrifuging. From the numbers and mean dimensions of the cells of each species present, the total cell volume of the phytoplankton in each sample was computed.

However, this method proved so laborious that in April 1947 a different procedure was adopted. The phytoplankton was sampled by measuring the chlorophyll concentration, with qualitative microscopic examination to identify the organisms present and only occasional quantitative estimation of cell numbers and volumes. For the chlorophyll determination the plankton in a one or two liter sample was concentrated by either of two methods: 1) by filtering in a modified Seitz filter through Whatman No. 42 paper covered with a layer of barium sulfate (Redfield, Smith and Ketchum, 1937), or 2) by using a Foerst continuous centrifuge, bringing the catch to dryness by filtering through barium sulfate on Whatman no. 42. The second method resulted in chlorophyll readings that were only about 95% as great as those obtained by the first method, but it required far less time. The remaining procedure for the chlorophyll determination is the same as that followed by Edmondson and Edmondson (1947: 231), who give the transmission spectra of the Klett filters no. 66 and no. 69 and discuss their use in chlorophyll measurements. The Klett-colorimeter and filter no. 66, with which chlorophyll concentrations in the present work were determined, were calibrated against the instrument and filter used by the Edmondsons. The amount of chlorophyll is expressed as milligrams of chlorophyll *a* per cubic meter.

The two methods of phytoplankton measurement are compared in Fig. 1, which shows the relation between chlorophyll concentration and calculated total cell volume in 43 pairs of duplicate samples which were analyzed by both procedures. The least squares line has been fitted to the data; the correlation coefficient is 0.908. This degree of agreement is surprising when one considers that the samples were taken during the months April–August from populations which varied in their species composition and physiological state. The sample showing an abnormally high chlorophyll/volume ratio (chlorophyll = 44.25 mg./m^3, volume = 4.136 ml./m^3) was collected on a day when unusually high wave action roiled the water. On the basis of unpublished work of Denis L. Fox (in litt.) it appears likely that phaeophytin and other chlorophyll derivatives, which are relatively stable and tend to accumulate in bottom muds and which absorb some light at 660μ, may have interfered with the chlorophyll determination in this sample.

Note that the agreement between the two methods is nearly as close at high values as at low. This is probably due to the fact that in all samples with a calculated total cell volume greater than 15 ml./m^3, by far the greatest fraction of the total volume was contributed by large

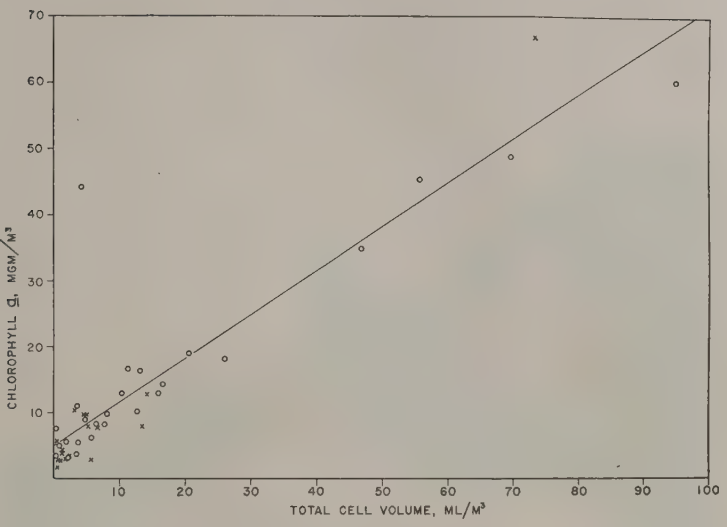

Figure 1. The relation between concentration of chlorophyll *a* and calculated total cell volume in 43 pairs of duplicate phytoplankton samples.
X's = samples preserved in 3% formalin before enumeration and measurement of cells. Circles = samples in which cells were counted and measured in the fresh state.

cells which probably belonged to the same species (genus *Peridinium*). The same predominance of apparently the same species of *Peridinium* in all other samples with a total cell volume greater than 15 ml./m^3 makes it fairly safe to conclude that had these samples been tested for chlorophyll they would have shown approximately the same volume to chlorophyll relationship as is illustrated in Fig. 1. This relationship is chlorophyll *a* (mg./m^3) = 5.035 + 0.6647 × volume (ml./m^3). In view of the high correlation between the two methods of plankton measurement and the desirability of presenting all the data in common units for the sake of intercomparison, all volumetric measurements will be expressed in terms of their chlorophyll equivalents, as calculated by this equation. Due to the quantity 5.035 in the equation, such a transliteration produces an artificial absence of chlorophyll values less than that number. But this distortion is not considered serious, since it affects only the lower and consequently less interesting range of values where the percentage of error is probably highest.

HYDROGRAPHY AND PHYTOPLANKTON

Little Harbor, an arm of the sea situated in Cohasset, Massachusetts, is connected with the open ocean by a narrow neck at its eastern end, as shown in Fig. 2. The northwest portion of Little Harbor, enlarged in Fig. 3, is the pond with which the present study is concerned.

Figure 2. Little Harbor, Cohasset, Massachusetts (traced from aerial photograph).

The narrow southern extremity, which is the pond's only connection with the main body of Little Harbor, is closed by a dam. The dam is provided with a check gate about ten feet long and three feet deep, which is suspended from a hinge in such a way that it is pushed inward and raised by the rising tide, admitting the inflowing water rapidly. The ebbing tide holds the check gate closed while pouring

out over the top of it; this continues only as long as the water level of the pond is higher than the top of the dam. As a result, the tide flows in for only about two hours and out for about ten hours. The average difference between high and low tide levels in the pond is only 0.22 m., while in other parts of Little Harbor this difference is nearly 3 m.

The area of the pond is 19.5 acres, or eight hectares. At low tide the mean depth is 0.54 m. and the volume about 42,000 m^3; on the mean high tide the mean depth is 0.75 m. and the volume about 59,000 m^3. Thus the water lost from the pond following a mean high tide is 30% of the high tide volume. At spring tides this proportion may be as high as 65%; during neap tides it is reduced to zero. Although a thorough hydrographic study was not attempted, a number of observations indicated that the flood tide water generally

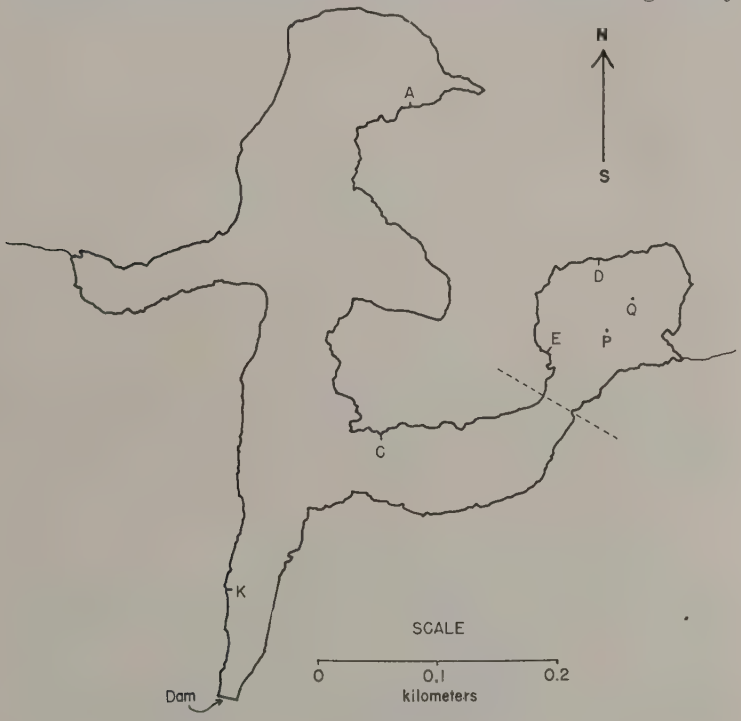

Figure 3. Northwest arm of Little Harbor.

tended to move in at all levels, pushing the old water back, so that the degree of mixing and exchange in the upper arms of the pond was not as great as the above figures would imply.

The two fresh-water streams which empty into the pond are both tidal, and at low tide the volume of water entering the pond from each of these is represented by a very slow-moving stream of about 1 ft² in cross-section. Thus the volume of water which they contribute to the pond is negligible as compared with that which enters with the tide. The bottom of the pond is covered for the most part with a thick layer of fine black mud which supports a heavy growth of Widgeon Grass (*Ruppia maritima*).

Temperatures, salinity and hydrogen-ion concentration were measured at least twice weekly from March to September 1946 and from March to September 1947, and at longer intervals from September 1946 to March 1947. The pond was covered with ice from mid-December to mid-February. Spring and summer temperatures were quite similar in 1946 and 1947 (Table I).

TABLE I. Seasonal Variations in Morning Surface Temperatures (in °C.)

	March–April			*May–June*			*July–Sept.*		
St.	*Mean*	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*
					1946				
A	10.0	6.5	14.0	15.5	10.3	19.4	21.6	16.1	26.2
E	9.7	6.0	15.0	16.4	11.6	19.2	21.9	16.9	26.4
K	9.9	6.4	14.5	16.0	12.6	19.8	21.1	16.8	25.8
					1947				
A	9.2	3.5	17.1	15.2	7.4	27.8	23.8	20.5	27.6
E	9.8	3.1	17.5	15.6	7.3	29.8	24.6	20.5	28.3
K	8.0	3.3	15.2	15.2	7.1	26.1	23.3	20.9	26.8

Between March and September (both years) there were no marked seasonal variations in the salinity, which fluctuated irregularly depending upon the amount of rainfall and the rate of evaporation. The normal range of this variation was 26.00 to 36.00 °/₀₀, rarely dropping to 20.00 °/₀₀ or slightly lower, and occasionally rising to nearly 40.00 °/₀₀.

At Station K, near the dam, the pH generally ranged between 7.8 and 8.2 with little perceptible seasonal change. In the upper arms of the pond the pH range was considerably wider, most readings falling between 7.8 and 8.6 with extremes of 7.1 and 9.1. From July through September the pH averaged about 0.5 unit higher than in the spring months.

In a study of the biological productivity of an aquatic area, obviously the quality as well as the quantity of the phytoplankton produced is an important consideration. Aside from the question of

noxious species such as those responsible for "red water," the different phytoplankton species doubtless vary in their nutritive value for the herbivores subsisting upon them, both in respect to chemical composition and to cell size. In our present state of ignorance regarding comparative nutritive values, a mere listing (Table II) of the plank-

TABLE II.—Photosynthetic Organisms Identified from the Pond, 1946 and 1947. (Numbers in parentheses indicate the order of frequency in which organisms occurred in the samples, e. g. *Navicula* was identified from a greater number of samples than was any other genus.)

Diatoms	Diatoms—Cont.	Flagellates	Chlorophyceae
Amphiprora (6)	*Distephanum*	*Eutreptia* (7)	*Carteria*
Chaetoceros (10)	*Fragillaria*	*Ezuviella* (5)	*Pyramimonas*
Navicula (1)	*Guinardia*	*Peridinium* (2)	*Scenedesmus*
Nitzschia (3)	*Gyrosigma*	*Prorocentrum* (8)	
Pleurosigma (4)	*Lichmophora*	*Ceratium*	Xanthophyceae
Skeletonema (9)	*Melosira*	*Ebria*	*Olisthodiscus*
Amphora	*Paralia*	*Euglena*	
Asterionella	*Rhizosolenia*	*Hymenomonas*	
Biddulphia	*Striatella*	*Kephyrion*	
Cocconeis	*Surirella*	*Lepocinclis*	
Coscinodiscus	*Thalassiosira*	*Mallomonas*	
Cyclotella	*Thalassiothrix*	*Ochromonas*	

tonic algae and colored flagellates identified from the pond will suffice for the purpose of this report. The ten genera most often represented are numbered in the order of the frequency of their occurrence in the samples.

In neither year was an early spring flowering observed, although it is possible that undetected blooms occurred before frequent sampling was begun in mid-March. In terms of volumes and chlorophyll concentrations, minor blooms occurred in April, May and June, but in both years the major blooms came in August and early September. *Peridinium* contributed usually four-fifths or more of the total cell volume in these latter blooms. In terms of volume this genus was the most important single fraction of the population throughout the year, except in the late spring blooms when it was largely replaced by small unidentified flagellates.

EXPERIMENTS

Six experiments, differing in design as to types of fertilizers used and number of applications, were conducted during the two years' work. Fertilizers were applied only during periods when the tidal exchange was small. The method of fertilizing consisted in broadcasting commercial fertilizers from a boat which was being rowed about in that part of the eastern arm of the pond which is north of the dotted line in Fig. 2. This section was designated the "fertiliza-

tion area." In the 1947 experiments, following each application, the boat was rowed about for half an hour to aid in the distribution of the fertilizers. The extreme northern part of the pond, represented by Station A, was termed the "control area." The nitrate fertilizers dissolved readily, whereas the superphosphate apparently sank to the bottom and went into solution slowly. The amounts and ratios in which the fertilizers were used were determined by various theoretical and practical considerations, and by the dictates of experience as the work progressed. It seemed desirable to increase the nutrient concentrations to values well above the maxima found in the sea (about 3 μg.-at. PO_4 P and 43 μg.-at. NO_3 N per liter; Sverdrup, Johnson and Fleming, 1942), while it was neither feasible nor desirable to approximate the concentrations employed in culture media for marine diatoms, such as 56 μg.-at. P and 1,100 μg.-at. N per liter in Ketchum and Redfield's (1938) modification of Miquel's solution. When nitrate and phosphate were applied simultaneously they were added in proportions intended to yield nitrate nitrogen and phosphate phosphorus in solution in the 16 : 1 atomic ratio in which they are taken up, on the average, in the open ocean (Sverdrup, Johnson and Fleming, 1942). It should be added, however, that the prefertilization ratio in the pond water varied between 0.48 : 1 and 45 : 1; the mean ratio was only 7.8 : 1.

In Table III the experiments are listed and briefly described. The last column of the table gives, for each application, the calculated increase in concentration of nutrients which theoretically should have resulted from that application.

A. Effects of Added Fertilizers upon Phosphate and Nitrate Content of the Water

1. Immediate Effect

a. *Phosphate.* In the five experiments in which superphosphate was used, the initial application theoretically should have increased the phosphate phosphorus concentration in the fertilization area by 25 μg.-at./l. Prior to the first application of fertilizers, the mean concentration in that area had been 0.38 μg.-at./l. The highest values recorded following initial applications occurred between one and seven hours after fertilizing. In these experiments the mean increase in the fertilization area ranged from 3.0 to 11.2 μg.-at./l.; the grand average of increase was 7.1 μg.-at./l. Since the pond was fertilized only during periods of reduced tidal exchange, the difference between theoretical and observed values cannot be attributed to tidal action. The probable explanation for this difference is that the

TABLE III.—Summary of Fertilizations by Date, Fertilizers Added, and Theoretical Increases of P and N Concentrations in the Fertilization Area

Expt.	*Date*	*Fertilizers Added*	*Theoretical Increases (see text)*
	1946		
1	Aug. 13	71 lbs. 20% superphosphate	25 μg.-at. PO_4P/l.
2	Aug. 26	132 lbs. NH_4NO_3	194 μg.-at. NO_3N/l.
3	Sept. 2	71 lbs. 20% superphosphate	25 μg.-at. PO_4P/l. and
		71 lbs. NH_4NO_3	194 μg.-at. NO_3N/l.
		61 lbs. $NaNO_3$	
	1947		
4	Apr. 28	30 lbs. 47% superphosphate	25 μg.-at. PO_4P/l.
	Apr. 30	15 lbs. 47% superphosphate	12.5 μg.-at. PO_4P/l.
	May 2	ditto	ditto
	May 5	ditto	ditto
	May 7	ditto	ditto
	May 9	ditto	ditto
5	July 21	30 lbs. 47% superphosphate	25 μg.-at. PO_4P/l. and
		54 lbs. $NaNO_3$	80 μg.-at. NO_3N/l.
	July 23	15 lbs. 47% superphosphate	12.5 μg.-at. PO_4P/l. and
		54 lbs. $NaNO_3$	80 μg.-at. NO_3N/l.
	July 25	ditto	ditto
	July 28	ditto	ditto
	July 30	ditto	ditto
	Aug. 1	ditto	ditto
	Aug. 4	54 lbs. $NaNO_3$	80 μg.-at. NO_3N/l.
	Aug. 6	ditto	ditto
6	Aug. 22	30 lbs. 47% superphosphate	25 μg.-at. PO_4P/l. and
		54 lbs. $NaNO_3$	80 μg.-at. NO_3N/l.
	Aug. 25	15 lbs. 47% superphosphate	12.5 μg.-at. PO_4P/l. and
		54 lbs. $NaNO_3$	80 μg.-at. NO_3N/l.
	Aug. 27	ditto	ditto
	Aug. 29	ditto	ditto
	Sept. 1	ditto	ditto

phosphate did not dissolve immediately from the fertilizer, although it is also possible that it went into solution only to be absorbed immediately on the bottom or taken up by the phytoplankton. These three possible explanations are not mutually exclusive, but the experience of Gross, *et al.* (1946) would seem to favor the first. Following their fertilization of Caol Scotnish with undissolved superphosphate (the technique employed at Cohasset), they estimated that not more than one-fourth of the phosphate in the fertilizer dissolved immediately at fertilization, but that some of the phosphate which sank to the bottom went into solution later. However, when these same investigators dissolved the superphosphate before applying it to Loch Craiglin, they detected much higher proportions of the theoretically expected values; indeed some of their readings exceeded the theoretical (Orr, 1947).

b. *Nitrate.* Nitrate was not measured in Experiments 2 and 3.

As will be seen below, however, the repeated application of nitrate (Experiments 5 and 6) had no cumulative effect upon its concentration in the open water. Therefore, each application in these experiments had an effect comparable to a single fertilization. The mean value for the fertilization area prior to Experiment 5 had been 3.4 μg.-at. NO_3N/l. In the 13 applications in Experiments 5 and 6, the average increase in concentration two hours later ranged from 24.6 to 123 μg.-at. N/l.; the grand average of increase was 80.5, which was the theoretically predicted increase. These results are comparable to those reported by Orr (1947). Thus the correspondence of the actual to the theoretical increase in nitrate concentration was, albeit irregular, closer than in the case of phosphate. This no doubt reflects the greater solubility of the nitrate fertilizer.

2. Duration of Effect

a. *Phosphate.* Because of the obvious risks in fertilizing a body of water subject to any degree of tidal exchange, the duration of the effects of fertilization is of great practical importance. Let us consider first the fate of added phosphorus following single applications of fertilizers. This was studied in Experiments 1 and 3 (Fig. 4). The time of fertilization is indicated by an arrow on the baseline. In each of these experiments the resulting phosphate maxima at the two stations within the fertilization area (D and E) differed widely; doubtless this was the result of imperfect distribution of the fertilizer. In both experiments phosphate at the various stations was affected in the order of their proximity to the fertilization area, in regard to both the intensity of the effect and its immediacy. At the control station (A), phosphate values during these experiments remained well within the limits observed prior to fertilization.

In Experiment 1, the effect of fertilization upon the phosphate content of the water lasted only one day; in Experiment 3 it lasted about one week. This difference cannot be laid to a difference in the rate of phosphate absorption by the phytoplankton, since the amounts of plankton present in the fertilization area during these experiments were very nearly identical. Moreover, in Experiment 3 the presence of added nitrate should have allowed a greater rate of phosphate absorption by the phytoplankton, for it is known that the rate of phosphate absorption depends upon the nitrate as well as the phosphate concentration (Ketchum, 1939a). Possibly the more rapid disappearance of phosphate from the water in the first experiment was due to a greater degree of adsorption by the bottom. The mud was thus saturated to the extent that when phosphate was again

applied 20 days later (Experiment 3) a greater amount of it remained in solution until removed by other agencies.

The increased phosphate concentrations resulting from single applications of superphosphate to Loch Craiglin by Gross and his coworkers usually lasted less than a week (Orr, 1947). In most of the experiments described in detail, added phosphate had largely disappeared in three or four days, although in the only experiment thus described which produced nutrient concentrations as great as those

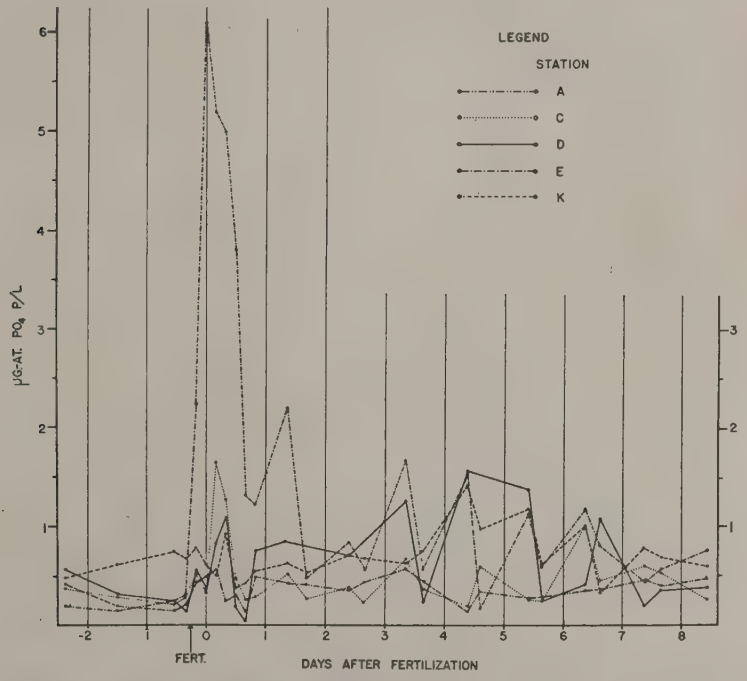

Figure 4. Inorganic phosphate concentration in the water following a single application of superphosphate fertilizer (Experiment 3).

produced at Cohasset, appreciable quantities of the added phosphate were detected about a week after fertilizing but had disappeared at the end of another week.

After applying the fertilizers in Experiment 3, phosphate readings were taken at least twice daily at about 9:30 a. m. and 3:30 p. m.

The vertical guide-lines in Fig. 4, spaced at 24-hour intervals, indicate midnight. It is evident that, following the fertilization, there was a diurnal fluctuation in phosphate values, with high readings in the morning and low readings in the afternoon. This was especially pronounced and persistent at the stations in the fertilization area, although at Station D the effect was somewhat obscured by the fact that on three afternoons the water level at this station was so low that it was impossible to get a sample. The degree of fluctuation can be expressed quantitatively as the ratio of the morning reading to the afternoon reading of the same day. The mean of these ratios for each station then provides a basis for comparison between stations. Expressed as factors, these averages are as follows: Station D, 7×; E, 3×; C, 1.5×; K, 1.3×. At Station A in the control area the factor is − 0.07×, indicating no significant fluctuation whatever. Thus the degree of fluctuation is consistently correlated with proximity to the fertilization area.

Newcombe (1940) has reported a somewhat similar diurnal phosphate pulse in the (unfertilized) waters of the Chesapeake Bay. The diurnal differences which he observed were of the order of 0.5 μg.-at. P/l., or about one-half as great as the diurnal differences discussed above. To account for this fluctuation Newcombe postulated a diurnal change in the phosphate metabolism of the phytoplankton, wherein phosphate is supposed to be released in large quantities by the plants during the night and reabsorbed during the day.

Since in the present work the diurnal pulse was correlated with proximity to the fertilization area, the facts here reported can be explained more easily on a different basis. It is suggested that the phosphate in the fertilizer, rather than dissolving immediately and all at one time, went into solution gradually over a period of several days. Presumably this occurred at a rate independent of the light intensity. While it is not known whether the phytoplankton was phosphorus deficient before the fertilization, Ketchum (1939b) has shown that only phosphorus deficient cells will take up phosphate in the dark, and his data make it seem nearly certain that if such a deficiency existed it would have been restored during the first day after fertilization. Assuming, then, no phosphorus deficiency after the fertilization, the more or less constant rate of solution of the fertilizer would allow a high phosphate concentration to accumulate during the hours of darkness when the phytoplankton was not photosynthesizing. During the day this concentration was then reduced by the activity of the plants. If suitable data were available on the rates of phosphate absorption in laboratory cultures, one might judge whether the phytoplankton would be capable of bringing about the

daily reduction in phosphate values, as proposed in this theory. The only published information on rates of phosphorus uptake appears to be that of Ketchum (1939a). Unfortunately, his *Nitzschia closterium* cells were so much smaller than the *Peridinium* cells which formed the bulk of the pond phytoplankton that one cannot predict the rate of absorption by *Peridinium* from Ketchum's data. However, there is some evidence to support the proposed explanation of the phosphate pulse. Throughout the period in which the pulse was observed, the total phytoplankton volume at Station D was very much greater than that at Station E (Fig. 7). While the phosphate record for Station D is admittedly incomplete, in so far as it goes, it indicates a considerably greater degree of diurnal fluctuation than that observed at Station E. This correlation between phytoplankton concentration and phosphate fluctuation is in accord with the above interpretation of the phosphate pulse.

However, in comparing Station E with the station in the control area one finds a negative correlation between phytoplankton concentration and phosphate pulse. At Station E phytoplankton volume was low and phosphate fluctuated greatly; at Station A the phytoplankton concentration was many times greater, yet no phosphate pulse was observed. This is explained by the much higher phosphate concentrations at Station E, which should increase the rate of phosphate absorption by the phytoplankton (Ketchum, 1939a).

If the phosphate pulse in the fertilization area results from the interaction of continuous supply and discontinuous consumption, the normal regeneration of phosphate in the control area and its absorption by the phytoplankton might be expected to produce a diurnal pulse of greatly reduced amplitude. That no pulse was observed indicates that either the amounts of phosphate regenerated nightly and absorbed daily were too small to produce a detectable diurnal variation, or that the phytoplankton, known to be extremely dense, was phosphorus deficient and therefore absorbed phosphate by night as well as by day.

In view of the rapid disappearance of phosphate following single applications, in the second year's experiments (Nos. 4, 5 and 6) the attempt was made to maintain nutrient levels of the order of 5 μg.-at. P/l. and (in the last two experiments) 80 μg.-at. N/l. by the repeated application of fertilizers. The results of Experiments 4 and 5 are shown in Figs. 5 and 6. Fertilizations are indicated by arrows, and for the sake of clarity the readings at Stations E, P and Q in the fertilization area have been averaged. Except in Experiment 4, the area represented by Station A appears to have served as a fairly

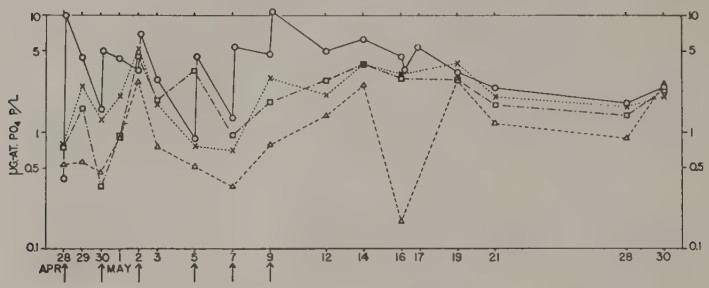

Figure 5. Inorganic phosphate concentration in the water during and following the repeated application of superphosphate fertilizer (Experiment 4). Arrows at bottom of figure indicate applications of fertilizer. Squares = Station K, triangles = Station A, X's = Station C, circles = mean of Stations E, P and Q.

effective control, in that the fertilizations influenced only slightly the nutrient concentrations in that area.

Experiment 6 was cut short by an unusually heavy rain on September 2 which lowered the salinity from about 34 °/₀₀ to values ranging from 7 to 16 °/₀₀ on September 3. Since the phytoplankton (chiefly *Peridinium*) was almost completely wiped out, it was decided to terminate the experiment.

In Experiments 4 and 5 a cumulative effect of repeated fertilizations upon phosphate values was clearly evident. Following the last application in Experiment 4, concentrations remained substantially above 1 μg.-at. P/l. at all stations for six weeks; in Experiment 5 the concentration in the fertilization area remained above that level for two weeks after the last application. This effect is believed to be due to the accumulation of phosphate reserves in the mud which were then given off gradually.

The more rapid disappearance of phosphate in Experiment 5 (also Experiment 6, not figured) than in Experiment 4 is probably related to its rate of absorption by the phytoplankton. Not only was the phytoplankton population denser in Experiments 5 and 6 than in Experiment 4 but, for three reasons, it seems likely that the *net* rate of assimilation was higher in these later experiments: 1) for the most part the weather was clear, whereas during Experiment 4 it had been consistently overcast; 2) the mean temperature was approximately 10° higher; and 3) the presence of added nitrate (lacking in Experiment 4) should have further stimulated photosynthesis and phosphate assimilation.

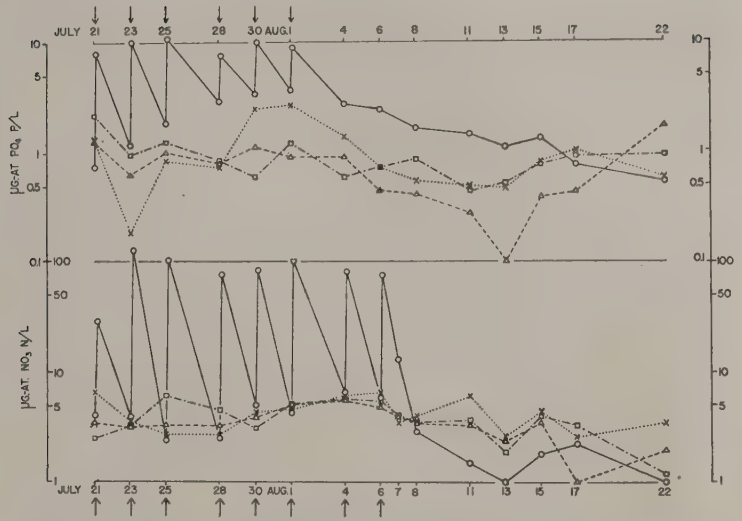

Figure 6. Concentrations of inorganic phosphate and nitrate during and following the repeated application of superphosphate and sodium nitrate fertilizers (Experiment 5). Arrows at top of figure indicate applications of superphosphate; arrows at bottom indicate nitrate applications. Squares = Station K, triangles = Station A, X's = Station C, circles = mean of Stations E, P and Q.

The diurnal phosphate pulse in the fertilization area was measured once in Experiment 4 (Fig. 5). Readings were made at 1 p. m. and at 4 p. m. on May 16 and again the following morning at 9, producing the sharp notch observed in the curve, which gives some idea of the magnitude of diurnal fluctuation. (The measurements on other days were made in middle or late morning, except for those following an application of fertilizers; these were made in midafternoon.)

b. *Nitrate.* The duration of effect of nitrate fertilizers upon nitrate concentrations in the water was observed in Experiments 5 and 6. Although the highly soluble sodium nitrate produced the theoretically predicted increase, it is clear from Fig. 6 that this high value could not be maintained, even when fertilizer was applied as often as eight times in 17 days. Only once was nitrate measured the day after a fertilization (Aug. 7, Fig. 6); on this occasion almost all the added nitrate had disappeared in 24 hours. The fate of this nitrate is not known. No doubt some of it was taken up by the phytoplankton, but the detection of hydrogen sulphide in the bottom mud suggests

that much of the nitrate may have undergone chemical reduction.

The distribution of added nitrate was well "controlled," in that it did not affect the concentrations at Stations A and K except toward the end of Experiment 6.

B. Effects of Added Fertilizers upon the Standing Crop of Phytoplankton

It is to be expected that the size of the phytoplankton standing crop may vary seasonally over a wide range, and that occasional blooms occur "spontaneously," *i. e.*, in the absence of artificially added nutrients. For this reason, and because in our present state of knowledge it cannot be assumed that all the effects of increased nutrient concentrations will be manifest immediately, it is necessary to coordinate in a single view the events of an entire season, in order to assess the effects of the experiments upon the phytoplankton. Phosphate concentration and phytoplankton volume (converted and expressed as chlorophyll *a*) at the stations in the fertilization area and at Stations A and K for March–September 1946 are shown in Fig. 7. For 1947 the variations in nitrate as well as phosphate are given in relation to the direct measurement of chlorophyll *a* (Fig. 8).

The central aim of the first year's experiments was to obtain information on the rate of phosphate disappearance. The repeated application of fertilizers was not attempted in 1946, and the response of the phytoplankton to single applications need not be discussed at any length. In the experiment involving a single application of phos-

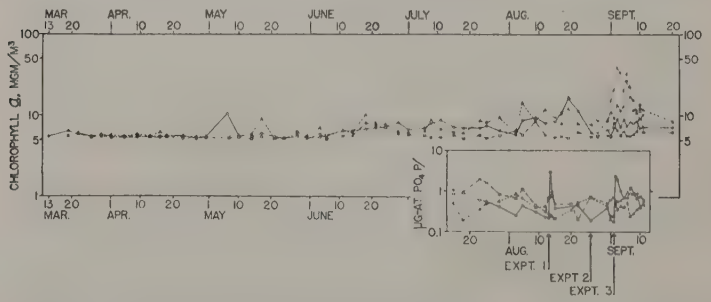

Figure 7. Phytoplankton and inorganic phosphate, 1946.

Squares = Station K; triangles = Station A; X's = Station D; Circles = phytoplankton for Station E and phosphate for fertilization area (Station E, July 15–August 13; mean of Stations E and D, Aug. 14–Sept. 11). Chlorophyll values computed from total cell volumes (see p. 39). Phosphate record Aug. 12–15 and Sept. 2–10 as daily averages only (for details of latter dates, see Fig. 4). The beginning of each experiment is indicated by an arrow at bottom of figure.

phate only (Experiment 1), the highest phytoplankton values observed at Station E in 1946 occurred six days after the fertilization. Values for Station D, also in the fertilization area, were in close agreement. However, a moderate flowering had started in the control area (Station A) a week prior to the experiment. It is quite possible, therefore, that the bloom in the fertilization area originated from causes affecting both arms of the pond and was independent of the fertilization. Six days after the single application of nitrate (Experiment 2), an intense but very local bloom developed in the vicinity of Station D and lasted one week. Station E was not affected, and again a presumably spontaneous bloom occurred in the control area. The single application of phosphate and nitrate (Experiment 3), which produced rather high phosphate values for one week in the fertilization area and at Station K, apparently had no effect upon the phytoplankton of the fertilization area, but may have produced the ephemeral flowering at Station K eight days later.

The 1947 experiments, involving the repeated application of fertilizers, were designed to show the effects upon the phytoplankton of nutrient concentrations maintained at high levels. The repeated applications of phosphate alone (Experiment 4) were made during a

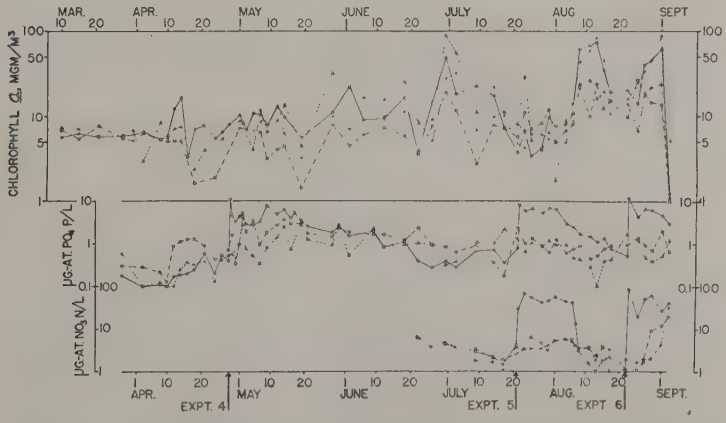

Figure 8. Phytoplankton, inorganic phosphate and nitrate, 1947.

Squares = Station K; triangles = Station A; X's = Station P; circles = phytoplankton for Station E; phosphate for fertilization area (Station E until April 26, mean of Stations E, P and Q thereafter). Chlorophyll values: for March computed from total cell volumes, thereafter measured directly. Phosphate record April 30–May 16, and phosphate and nitrate July 23–Aug. 6 and Aug. 25–Sept. 1 as daily averages only (for details see Figs. 5 and 6). The beginning of each experiment is indicated by an arrow at bottom of figure.

period of consistently cloudy weather and had no immediate influence on the size of the standing crop. It should be noted that during and particularly following this series of fertilizations, phosphate reached high values in all parts of the pond, and had hardly returned to the early spring level (approximately 0.5 μg.-at. P/l.) when Experiment 5 was started on July 21. In the first half of June there was some increase in phytoplankton at Station E and a more sustained bloom at Station A, which in this experiment did not serve as a control. At the end of June the flowering spread to all areas and attained roughly twice the magnitude of the 1946 maximum. If the increased phosphates resulting from Experiment 4 played any part in this June blooming, other factors (*e. g.* light) must have been equally important, since the bloom did not start until one month after the beginning of the experiment.

The repeated applications of phosphate and nitrate in Experiment 5 affected nutrient concentrations in the fertilization area only. A very heavy bloom developed there, starting 16 days after the beginning of the experiment. At the same time the populations at Stations A and K increased to about one-third the density in the fertilization area. The distribution of phytoplankton was then equalized again, at a rather high concentration, by the high tides of August 11–21.

When the same fertilizers were again added in Experiment 6, the phytoplankton at Stations A and K continued to oscillate about the same general level, while that in the fertilization area immediately began to bloom heavily and reached the same density attained in Experiment 5. The experiment was cut short on the thirteenth day (September 3) when virtually all phytoplankton, as judged by chlorophyll analyses, had disappeared from the surface layers as a result of the rainstorm of the previous day.

DISCUSSION

The widespread flowering one month after the beginning of Experiment 4 and the bloom in the fertilization area 16 days after the start of Experiment 5 suggest the possibility of a delayed effect of fertilization upon the growth of the phytoplankton. An "initial lag" period preceding the increase in standing crop is a phenomenon of population growth among unicellular organisms that is as well known as it is poorly understood. Phelps (1935) demonstrated such a lag in laboratory populations of the ciliate *Glaucoma pyriformis* and compared it with the lag long known to occur in bacterial cultures. Riley (1943) observed the same phenomenon in mixed diatom populations taken directly from the sea, and a lag lasting up to 15 days in the growth of some of his *Nitzschia closterium* cultures in sea water en-

riched with commercial fertilizers. He interprets the relatively high proportion of senile cells and high rates of respiration and photosynthesis during the lag in his *Nitzschia* cultures as indicating that the lag is a period of rapid growth and rapid death. The delayed blooming of fertilized fresh-water ponds is a problem familiar to fisheries workers. According to Swingle (1947), the experimental ponds at Auburn, Alabama, normally bloom within one to three days after fertilizing with nitrogen, phosphorus, and potassium, but in some cases the flowering is delayed for as long as one month.. During such a lag the plankton did not respond to any of a variety of treatments, including artificial aeration of the water, inoculation with actively growing algae, addition of minor nutrient elements (zinc, manganese, iron, iodine, boron and copper) and addition of vitamins B_1 and B_6. Swingle attributes the lag in some cases to organic bottom deposits, with whose associated bacterial flora the autotrophic plankton could not compete for inorganic nutrients; other cases he assigns to a lack of sufficient carbon dioxide. It does not seem likely that either of these proposed explanations could be applied to the "delayed" blooms here described. Swingle's first hypothesis requires that the added nutrients be almost entirely consumed by the bacteria, whereas in the present experiments an abundant supply of dissolved phosphate remained throughout the "lag" periods. The great excess of bicarbonate present in sea water and the undetermined but presumably high rate of carbon dioxide evolution from decomposing organic deposits would seem to preclude the possibility of a carbon dioxide shortage.

The question naturally arises as to whether the eventual flowering of a fertilized pond, following a lag, is or is not related to the fertilization. The magnitude of the growth which follows a lag in laboratory cultures, such as Riley's *Nitzschia*, is a function of the nutrient concentration at the start of the experiment, and it is implicit in Swingle's report on fertilized ponds that the bloom following even a month's lag is related to the fertilization in the same manner. This implication must depend upon the observation that the delayed bloom is greater (in intensity, duration, or both) than spontaneous blooms occurring in unfertilized ponds. This comparison would appear to provide the only standard of judging whether a delayed bloom owes its magnitude to the fertilization. Applying this criterion to the "delayed" blooms in the Cohasset pond (June and early August 1947), one notes that the first of these endured much longer than any previous bloom and that both reached maxima two times as great as had been observed before. Therefore it seems quite probable that the fertilizations of Experiments 4 and 5, respectively, were

responsible for the magnitude of these blooms. The June flowering may well have been delayed, at least in part, by the lack of sufficient sunlight during the cloudy month of May. To explain the 16 day lag in Experiment 5 we must look to other causes, for the weather was clear throughout this period. It seems likely that some undetected environmental factor affecting the entire pond was unfavorable during this interval; a change in this factor then permitted a moderate amount of growth at Stations A and K and a dense bloom in the area rich in phosphorus and nitrogen.

A discussion of the immediate and delayed results of individual experiments does not exhaust all the possible effects of fertilization upon the standing crop of phytoplankton. Figs. 7 and 8 considered together show that, in so far as the conversion of volumetric data into chlorophyll equivalents is reliable, the average standing crop was appreciably greater after May 1947 than before. It is possible that this increase was quite independent of our manipulations, but the enrichment of the entire pond with phosphate resulting from the May fertilizations strongly suggests a cumulative effect of at least the last three experiments upon the growth of the phytoplankton.

To summarize regarding the effects of fertilization upon the phytoplankton, the results of the first three experiments do not permit any conclusions, Experiments 4 and 5 may have produced more or less delayed effects, Experiment 6 was followed by an immediate increase, and the second season's fertilizations collectively appear to have raised the general level of phytoplankton abundance for the entire summer. These results are quite similar to those obtained in the Loch Craiglin investigations (Marshall, 1947), which involved eleven fertilizations between August 1942 and March 1944. There is good evidence that three of these (Dec. 30, 1942, Sept. 1 and Nov. 5, 1943) produced immediate increases in the nannoplankton (although not in the diatoms or dinoflagellates), and the last three fertilizations appear to have had somewhat delayed but more lasting effects upon the diatoms and especially the dinoflagellates. The latter were more abundant in 1943 than in 1942 and increased further in 1944, apparently showing a cumulative effect of the successive fertilizations.

A sustained increase in the phytoplankton standing crop, such as is suggested in both the Cohasset and Loch Craiglin studies, would doubtless accelerate the productivity of the area at all trophic levels more effectively than would the same total production of phytoplankton apportioned in alternating periods of abundance and scarcity. This is the basis, in fresh-water fish-pond management, for the practice of applying fertilizers in small amounts at frequent intervals (Swingle and Smith, 1938). Some idea of the possible duration of

fertilization effects is gained from the experience of Einsele (1941). Superphosphate fertilizations of a fresh-water lake in the summer of 1938 produced, in the summer of 1939, total phosphorus and phytoplankton concentrations considerably greater than those found in the years prior to 1938.

In general, the rate of disappearance of added phosphate in the Cohasset experiments appears to have been a function of the abundance of phytoplankton. Note the acceleration of its disappearance with the plankton increase at the end of June 1947 and its much more rapid decrease during Experiment 5 than in Experiment 4. Furthermore, the densest phytoplankton populations coincided with, or followed closely upon, periods of maximum phosphate concentration, and the combined effects of the last three experiments appear to have brought about a long-term increase in the standing crop.

SUMMARY

1. The application of commercial superphosphate fertilizers to a salt water pond partially cut off from the sea raised the phosphate content of the water by approximately one-third of the theoretically calculated increase. Phosphate concentrations several times as high as the prefertilization values were maintained for several weeks by the addition of superphosphate in six applications over a period of two weeks.

2. Following an application of superphosphate, phosphate concentration in the area fertilized exhibits a diurnal pulse, which is believed to result from the continuous solution (day and night) of the fertilizer phosphate combined with a discontinuous absorption (in the daylight hours only) by the phytoplankton.

3. The application of commercial sodium nitrate raised the nitrate concentration of the water by the theoretically calculated increase. However, nitrate concentrations could not be maintained above the prefertilization values for more than 24 hours, even by the repeated application of sodium nitrate every second day.

4. The artificially increased concentrations of phosphate and nitrate resulted in increases in the standing crop of phytoplankton to several times the prefertilization maximum. This effect was realized within a few days, or after an initial lag of two to four weeks. The several fertilization experiments collectively appear to have produced a significant increase in the standing crop which lasted throughout the second summer of fertilizing.

REFERENCES

Edmondson, W. T. and Y. H. Edmondson
1947. Measurements of production in fertilized salt water. J. Mar. Res., *6:* 228–246.

Einsele, W.
1941. Die Umsetzung von zugeführtem, anorganischem Phosphat im eutrophen See und ihre Rückwirkungen auf seinen Gesamthaushalt. Z. Fisch., *39:* 407–488.

Evermann, B. W.
1904. The Oyster, In, Report on inquiry respecting food-fishes and the fishing grounds. Rep. Comm. Fish. (1903–1904), 81–84.

Gaarder, Torbjørn
1932. Untersuchungen über Produktions- und Lebensbedingungen in norwegischen Austern-Pollen. Bergens Mus. Aarb., Naturv. rek., Nr. *3:* 1–64.

Gaarder, T., and E. Alvsaker
1941. Biologie und Chemie der Auster in den norwegischen Pollen. Bergens Mus. Aarb., Naturv. rek., Nr. *6:* 1–236.

Gaarder, T., and R. Spärck
1932. Hydrographisch-biochemische Untersuchungen in norwegischen Austern-Pollen. Bergens Mus. Aarb., Naturv. rek., Nr. *1:* 1–144.

Gross, F.
1947. An experiment in marine fish cultivation: I. Introduction. Proc. roy. Soc. Edinb., (B) *63:* 1–2.

Gross, F., J. E. G. Raymont, S. R. Nutman and D. T. Gauld.
1946. Application of fertilizers to an open sea loch. Nature, Lond., *158:* 187–189.

Ketchum, B. H.
1939a. The absorption of phosphate and nitrate by illuminated cultures of Nitzschia closterium. Amer. J. Bot., *26:* 399–407.
1939b. The development and restoration of deficiencies in the phosphorus and nitrogen composition of unicellular plants. J. cell. comp. Physiol., *13:* 373–381.

Ketchum, B. H., and A. C. Redfield
1938. A method for maintaining a continuous supply of marine diatoms by culture. Biol. Bull. Woods Hole, *75:* 165–169.

Marshall, S. M.
1947. An experiment in marine fish cultivation: III. The plankton of a fertilized loch. Proc. roy. Soc. Edinb., (B) *63:* 21–33.

Newcombe, C. L.
1940. Studies on the phosphorus content of the estuarine waters of the Chesapeake Bay. Proc. Amer. phil. Soc., *83:* 621–630.

Orr, A. P.
1947. An experiment in marine fish cyltivation: II. Some physical and chemical conditions in a fertilized sea-loch (Loch Craiglin, Argyll). Proc. roy. Soc. Edinb., (B) *63:* 3–20.

Phelps, Austin
1935. Growth of protozoa in pure culture. 1. Effect upon the growth curve of the age of the inoculum and of the amount of the inoculum. J. exp. Zool., *70:* 109–130.
Redfield, A. C., H. P. Smith and B. H. Ketchum
1937. The cycle of organic phosphorus in the Gulf of Maine. Biol. Bull. Woods Hole, *73:* 421–443.
Riley, G. A.
1943. Physiological aspects of spring diatom flowerings. Bull. Bingham Oceanogr. Coll., *8* (4): 1–53.
Sverdrup, H. U., M. W. Johnson and R. H. Fleming
1942. The Oceans. Prentice-Hall, Inc., New York. 1087 pp.
Swingle, H. S.
1947. Experiments on pond fertilization. Bull. agric. Exp. Sta. Ala. Poly. Inst., No. 264.
Swingle, H. S., and E. V. Smith
1938. Fertilizers for increasing the natural food for fish in ponds. Trans. Amer. Fish Soc., *68:* 126–135.
Wattenberg, H.
1937. Critical review of the methods used for determining nutrient salts and related constituents in salt water, 1. Rapp. Cons. Explor. Mer., *103:* 1–26.
Zwicker, B. M. G. and R. J. Robinson
1944. The photometric determination of nitrate in sea water with a strychnidine reagent. J. Mar. Res., *5:* 214–232.

Contribution No. 468

Reprinted from JOURNAL OF METEOROLOGY, Vol. 6, No. 2, April, 1949, pp. 123–133
Printed in U. S. A.

VERTICAL EDDY TRANSFER OF HEAT AND WATER VAPOR IN STABLE AIR

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Harvard College Observatory[1, 2]

(Manuscript received 6 August 1948)

ABSTRACT

Detailed soundings of temperature and humidity between the surface and 1000 ft in warm air moving over cooler water are studied to determine the vertical transfer of heat and water vapor due to turbulence. Under simplifying assumptions, values of the eddy diffusivity are determined from the data at several heights and distances from shore and under varying wind and stability conditions. A simple model, in which the eddy diffusivity increases linearly with height in the lowest meter or two and is independent of height at higher levels, is shown to be consistent with the observations.

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1. Introduction

The observations on which this paper is based consist of detailed soundings of temperature and humidity in the lowest 1000 ft of the atmosphere over Massachusetts Bay. They were obtained in the summer and fall of 1944 by means of an electrical-resistance psychrograph mounted on aircraft. The observational program was carried out under the general direction of Donald E. Kerr of the Radiation Laboratory, Massachusetts Institute of Technology, in connection with studies of the propagation of radio waves near the sea surface.

Details concerning the observational program may be found elsewhere. In particular, a book now in preparation (Kerr, 1949) contains a detailed discussion of the propagation problem, of the related meteorological problems, and of the observational techniques used to make the soundings. The instrument used is described by Katz (1947). Two short, qualitative discussions of the propagation problem and its relation to meteorology have been given by Sheppard (1946) and Montgomery (1947). Of the nearly 500 soundings made over Massachusetts Bay, 51 examples have been published together with discussion of the meteorological connotations of each (Craig, 1946). Two other papers discuss applications of the data to sea breezes (Craig *et al.*, 1945) and convection (Craig, 1947).

The present paper is concerned with the effect of eddy diffusion in changing the temperature and humidity of air leaving land and passing as far as 30 miles over cooler water. The air in direct contact with the water assumes the temperature of the water surface and, furthermore, assumes a vapor pressure equal to the saturation vapor pressure[3] at the temperature of the water surface. Thus, vertical gradients of temperature and humidity occur and result in turbulent transfer of heat and water vapor in the hydrostatically stable air. A limited number of the soundings made over Massachusetts Bay are suited to a detailed study of this process.

2. Modification cross sections

The soundings used in the study sampled air which had been homogeneous, or completely mixed, before leaving land; the potential temperature and specific humidity were then independent of height in the air before it passed over the water. The changes which occurred in the air during its over-water travel were determined by comparing the sounding with the simple initial distributions of temperature and humidity. Fig. 1 illustrates a schematic sounding, similar to the ones actually measured.

Moreover, the soundings that were used represented cases where the air had passed over water of uniform temperature and where, further, the effects of radiation from the air and of the shear of the air column due to

[1] Contribution No. 468 from the Woods Hole Oceanographic Institution.

[2] The data used in this paper were obtained for the office of Scientific Research and Development under contract OEM sr-262 with the Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts. Much of the preparation of the paper was carried out at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts as part of a contract (NObs-2083) with the Bureau of Ships, Navy Department. The paper has been completed at the Harvard College Observatory.

[3] Over salt water with salinity 35 per mille, the vapor pressure is approximately 98 per cent of the value over fresh water of the same temperature.

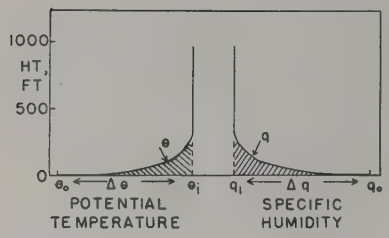

FIG. 1. Schematic example of soundings used in the present study. Air with initial potential temperature θ_i and specific humidity q_i passes over cooler water having temperature θ_0 and saturation specific humidity q_0 and assumes the stratification shown by the solid lines. The shaded areas represent the changes in temperature and humidity during the air's over-water travel.

the variation of wind velocity with height had been small in comparison with the effects of diffusion. The criterion for this selection was that the temperature and specific humidity in the modified air had each changed by the same proportion of the total possible change at each height. In terms of the symbols used in fig. 1,

$$p \equiv \frac{\theta_i - \theta}{\theta_i - \theta_0} = \frac{q_i - q}{q_i - q_0}, \qquad (1)$$

where p is called the *proportional change*. Eddy diffusion tends to produce this condition, because heat and water vapor are transported vertically to the same relative degree. On the other hand, radiation changes only the temperature of the air and not the specific humidity, and, hence, tends to make the proportional change at each level somewhat different for temperature than for humidity. Shear and variations in water temperature also tend to make (1) untrue. Further discussion of these points may be found elsewhere (Kerr, 1949, chap. 3; Craig, 1946, p. 10); for present purposes it is sufficient to say that the soundings used in this study show changes caused primarily by eddy diffusion over water of essentially uniform temperature.

TABLE 1. Soundings used on modification cross sections.

Group	Sounding designator	Date in 1944	Temp. excess (F)	Wind speed at 1000 ft (mi hr^{-1})	Wind force at surface (Beaufort)	Distance from land (miles*)	Where published C = Craig (1946) K = Kerr (1949)
I	Average	—	4.2	26	4	—	—
	A156	29 Sep.	3.4	28	4	8	K, 3.31†
	C236	23 Oct.	4.9	23	3	10	Not publ.
	A142	22 Sep.	3.8	25	4	25	K, 3.32
	B14	18 Aug.	4.6	30	5	45	C, 24
II	Average	—	6.5	15	3	—	—
	C199	26 Sep.	6.9	15	3	3	C, 42
	C200	26 Sep.	6.1	15	3	13	C, 43
	C201	26 Sep.	6.6	15	3	25	C, 44
III	Average	—	7.5	22	3	—	—
	C235	23 Oct.	7.5	21	3	2½	Not publ.
	C140	30 Aug.	7.8	21	3	10	C, 31
	A120	8 Sep.	7.7	22	—	24	C, 37
	A71	19 July	7.0	25	3	28	K, 3.33
IV	Average	—	9.9	23	3	—	—
	C136	29 Aug.	8.2	25	2	2	Not publ.
	A119	8 Sep.	11.9	20	—	8	C, 36
	C137	29 Aug.	9.4	25	3	9	Not publ.
	C143	30 Aug.	11.6	22	2	14	C, 32
	A69	19 July	10.6	24	3	18	Not publ.
	A70	19 July	9.0	21	3–4	21	K, 3.35
	C141	30 Aug.	8.4	22	3	26	K, 3.14
V	Average	—	10.0	14	2	—	—
	C150	2 Sep.	11.5	15	2	2½	Not publ.
	C144	31 Aug.	10.1	16	1	8	C, 33
	C151	2 Sep.	9.4	13	2	10	Not publ.
	C149	1 Sep.	9.7	13	2	24	C, 34
	C37	1 July	8.4	15	2	30	K, 3.34
	C152	2 Sep.	10.6	15	3	36	K, 3.16
VI	Average	—	12.4	35	4	—	—
	C229	19 Oct.	13.0	30	4	2	C, 7
	C118	21 Aug.	15.0	40	3	8	K, 3.38
	C230	19 Oct.	10.9	35	4	9	K, 3.36; C, 8
	C119	21 Aug.	12.0	35	4	12	C, 25
	C231	19 Oct.	11.0	35	4	23	K, 3.37; C, 9
VII	Average	—	18.0	18	2	—	—
	C104	15 Aug.	17.4	18	2	2	C, 20
	C227	18 Oct.	18.6	18	2	3	K, 3.19; C, 5

* Statute miles are used throughout this paper.
† Numbers in this column indicate fig. numbers in C or K.

For soundings of the type described above, the over-water modification depends on conditions that can be effectively described by three independent variables. These are the distance the air has traveled over the water, the temperature excess (potential temperature in the unmodified air less temperature of the water surface), and the wind speed at some chosen height, in this case, 1000 ft. These variables have been estimated for each sounding, during an analysis in which each sounding was considered individually in relation to measurements of water temperature, surface data from near-by land stations, and pilot-balloon and radiosonde observations in the region.

The wind speed and the temperature excess (the latter indicating the stability) determine the amount of mechanical turbulence in the air passing over water. Hence, the soundings have been divided into seven groups, each group consisting of soundings with nearly uniform values of wind speed and temperature excess. For each group the modification at various distances from shore is shown on a *modification cross section*, having distance from land as abscissa and height above the surface as ordinate. On each cross section, values of the proportional change are plotted at the distances from land where soundings were made and at the heights where readings were taken in the soundings. These heights were usually 20 ft, 50 ft, 100 ft, 150 ft, 200 ft and multiples of 100 ft up to 1000 ft. Immediately following a sounding up to 1000 ft, a second check sounding was made up to 500 ft. Hence, below 500 ft, four values of the proportional change (two each for temperature and humidity) were available at each level. These were nearly equal for the soundings used in this study and were averaged to obtain the values used in the modification cross sections.

Pertinent data for each sounding used in the cross sections are presented in table 1. The groups are listed in order of increasing temperature excess. The letter and number identifying each sounding follow a system used during the measuring program. The water temperature, necessary to determine the temperature excess, follows in some cases from measurements, in others from deductions based on the sounding itself (see Craig, 1946, p. 10). The wind speed at 1000 ft was estimated on the basis of pilot-balloon observations at near-by land stations, while the wind force at the surface was estimated by an observer in an airplane at the time and place of the sounding. The distance from land was obtained by tracing the air back according to the wind speed and direction at 1000 ft, to the point where it had left land. Most of the soundings have been published elsewhere (as indicated in the last column), in a form which shows the temperature and dew-point distributions in the vertical direction and which shows the degree of agreement between the first and the check soundings. It will be noted that the soundings in each group were not necessarily made on the same day.

The modification cross sections are shown in fig. 2. Not enough soundings are available to gain a continuous picture of the modification from the shore to the farthest sounding. However, two isopleths are drawn on each cross section to facilitate comparison among the seven groups; their positions are somewhat doubtful. It is apparent that the data are not entirely consistent, as may be seen, for example, by comparing pairs of soundings on the same cross section at nearly the same distance from shore. This lack of consistency is to be expected in view of possible instrumental errors, of errors involved in estimating parameters such as the distance from shore, and of the finite spread of temperature excess and wind speed within each group. Nevertheless, these data are sufficiently accurate and consistent to yield reliable empirical information about the modification in air passing a short distance over cooler water under varying conditions.

The height to which the air is noticeably affected during its over-water travel depends markedly on the wind speed and temperature excess. This is best seen by a comparison of group I with group V (fig. 2); in the former case, the temperature excess is the smallest among the groups and the wind is comparatively strong, while, in the latter case, the wind is comparatively light and the temperature excess large. For groups II, III, IV, and VI an intermediate effect is apparent, as might be expected qualitatively from the temperature excesses and wind speeds associated with them. There are insufficient data in group VII to draw any conclusions. While these facts are apparent from inspection of the cross sections, it is best to defer further comparisons among the groups until section 4, where some quantitative results are obtained from the data.

3. Parameters describing eddy transfer

The atmosphere, except for a thin layer of the order of 1 mm in thickness near the surface, is characterized by turbulent flow. Vertical transfer of heat or water vapor is accomplished largely by *eddies*, parcels of air which are displaced vertically and mix with their new surroundings. The vertical transfer, then, is clearly proportional to the vertical gradients of temperature and humidity. The *eddy diffusivity*, K, may be defined by

$$E = -\rho K \, \partial q/\partial z, \qquad (2)$$

where E is the upward flux of water vapor per unit area, ρ is the density of the air, and q is the specific humidity. The eddy diffusivity, K, has the dimensions L^2T^{-1}. It is defined in (2) in terms of the transfer of water vapor. At the same time and place, however, it is

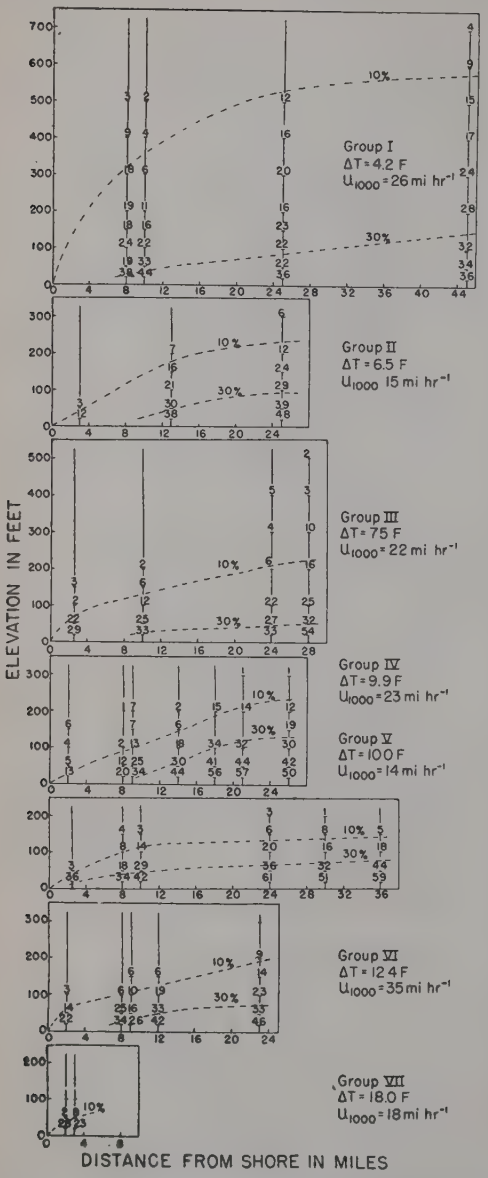

FIG. 2. Modification cross sections for several combinations of temperature excess (ΔT) and wind speed at 1000 ft (u_{1000}). The numbers plotted along the vertical for each sounding represent the proportional change in per cent and are based on observations of both temperature and humidity.

essentially the same for heat as for water vapor and may alternately be defined by

$$H = -\rho c_p K \, \partial\theta/\partial z, \tag{3}$$

where H is the upward heat flux per unit area, c_p is the specific heat, and θ is the potential temperature.

The eddy diffusivity, unlike the molecular diffusivity, is a property of the flow and not of the fluid. Its value in air varies widely, depending on height above the boundary surface, wind speed, and the degree of hydrostatic stability of the air. In many cases it may be considered equal to the *eddy viscosity*,[4] defined in an analogous manner in terms of the upward flux of momentum and the vertical gradient of wind. Determinations of both eddy viscosity and eddy diffusivity show that, except very near the surface, molecular diffusivity, conductivity, and viscosity may be neglected in the atmosphere.

Observations of vertical humidity gradients near the sea surface have shown that, at least in the lowest few meters, the specific humidity varies linearly with the logarithm of height (Montgomery, 1940; Sverdrup, 1946). Little error is introduced by assuming that in a shallow layer near the surface the vertical transfer of water vapor is independent of height and equal to the evaporation from the sea surface; this assumption merely neglects the water-vapor capacity of the shallow layer compared with the entire layer throughout which the water vapor is diffused. For these conditions, it follows from (2) that eddy diffusivity varies linearly with height above the surface. The thickness of the layer in which this linear law holds varies widely, and in any specific case is doubtful. For neutral hydrostatic equilibrium, Rossby and Montgomery (1935, p. 16) have shown that it is proportional to the wind speed and depends on the character of the surface; for a wind of 10 mph, it is of the order of 100 ft. Only a little direct evidence is available for cases where the air is in stable hydrostatic equilibrium. Sverdrup (1936), from a consideration of measurements made in stable air, concludes that the eddy diffusivity in the meter or two nearest the ground is not affected by stability. At greater heights above the surface, however, he finds values smaller than those for neutral equilibrium, the difference increasing with height.

Montgomery (1940) has introduced a dimensionless quantity Γ, called the *evaporation coefficient*. It varies somewhat with height and, when referred to a standard level b in the logarithmic layer, is defined by

$$\Gamma_b \equiv -\frac{1}{q_0 - q_b} \frac{\partial q}{\partial \ln z}, \tag{4}$$

where q_0 is the specific humidity at the sea surface and q_b is the specific humidity at the level b. Within this same layer, as has been pointed out, the eddy diffusivity varies linearly with height. This variation may

[4] However, they are apparently not equal very near a hydrodynamically rough surface or in very stable air. For a discussion of this point, see Kerr (1949, sec. 3–11) and Sverdrup (1938).

be represented by[5]

$$K = \kappa\gamma_b u_b z, \tag{5}$$

where κ is the turbulence constant, γ_b is the resistance coefficient referred to a standard level b within the logarithmic layer, and u_b is the wind speed measured at the same level b. This standard level is taken to be the same as that for (4). The product $\gamma_b u_b$ is independent of height. It follows from (2, 4, 5) that

$$E = G_b \rho u_b (q_0 - q_b), \tag{6}$$

where G_b is a dimensionless quantity given, to the extent that (5) is applicable, by

$$G_b = \kappa\gamma_b\Gamma_b. \tag{7}$$

4. Numerical values of eddy diffusivity and evaporation derived from the observations

Under certain simplifying assumptions, values of K, E, and G_b may be derived from the data in the modification cross sections. Consider a cube of unit volume situated at a horizontal distance x (along the direction of the wind) from shore and at a vertical distance z from the sea surface. The mass of water vapor in the cube may be affected by any one of three factors, namely, vertical eddy transfer, transfer by a net vertical velocity component, or transfer by advection. For a steady state (which the check soundings indicated for the data used in the modification cross sections),

$$\frac{\partial}{\partial z}\left(\rho K \frac{\partial q}{\partial z}\right) = \rho\left(w\frac{\partial q}{\partial z} + u\frac{\partial q}{\partial x}\right). \tag{8}$$

Here, w is the vertical velocity component, u is the horizontal velocity component, and ρ is the density. Advection takes place only in the x-direction, since the x-axis is taken in the direction of the wind.

If (8) is integrated between the levels z and Z,

$$\left(\rho K\frac{\partial q}{\partial z}\right)_Z - \left(\rho K\frac{\partial q}{\partial z}\right)_z = \bar{\rho}\int_z^Z \left(w\frac{\partial q}{\partial z} + u\frac{\partial q}{\partial x}\right) dz,$$

where $\bar{\rho}$ is an effective mean density between z and Z. The upper limit Z may be taken high enough so that, for practical purposes, $\partial q/\partial z = 0$. Since ρ and K are finite,

$$\left(\rho K\frac{\partial q}{\partial z}\right)_z = -\bar{\rho}\int_z^Z \left(w\frac{\partial q}{\partial z} + u\frac{\partial q}{\partial x}\right) dz. \tag{9}$$

If the lower limit is at the sea surface, the left side represents the evaporation from the sea surface, so that

$$E = -\bar{\rho}\int_0^Z \left(w\frac{\partial q}{\partial z} + u\frac{\partial q}{\partial x}\right) dz. \tag{10}$$

In view of (6),

$$G_b u_b = -\frac{1}{(q_0 - q_b)}\int_0^Z \left(w\frac{\partial q}{\partial z} + u\frac{\partial q}{\partial x}\right) dz, \tag{11}$$

where the assumption has been made that $\rho = \bar{\rho}$.

If the lower limit is not at the sea surface, (9) gives for K at the height z,

$$K_z = -\left(\frac{\partial q}{\partial z}\right)_z^{-1}\int_z^Z \left(w\frac{\partial q}{\partial z} + u\frac{\partial q}{\partial x}\right) dz, \tag{12}$$

where the assumption has been made that $\rho_z = \bar{\rho}$.

The term containing the vertical velocity component w in each of (10–12) cannot be evaluated from the data available. Furthermore, it is not necessarily negligible compared with the term containing u, because, even though w is presumably much less than u, $\partial q/\partial x$ is much less than $\partial q/\partial z$. The sign of the vertical velocity term follows from a consideration of the velocity divergence.

$$\partial u/\partial x + \partial w/\partial z = 0 \tag{13}$$

if the density is constant. While the wind observations made during the Massachusetts Bay program were too few and too coarse to determine the magnitude of $\partial u/\partial x$, observations of the surface wind indicated that it was usually negative but sometimes positive. In the former case, the vertical velocity must have been directed upward, and in the latter case, downward.

Since the term containing the vertical component of velocity cannot be evaluated, it is neglected in evaluating E, G_b, and K. This procedure is suitable as a first approximation because, of the three processes represented in the formulation of (8)—vertical eddy diffusion, vertical motion, and horizontal motion—vertical motion is the only one not essential in the formation of the patterns represented on the modification cross sections. Eddy diffusion and vertical motion alone would not suffice, because vertical motion without horizontal motion would not permit continuity. Vertical motion and horizontal motion alone would agree with the patterns to whatever extent the streamlines coincide with the lines of equal proportional change, but complete coincidence is impossible because the streamlines cannot all originate from the same point. Eddy diffusion and horizontal motion, however, can alone lead to the observed distributions. The values obtained should be of the correct order of magnitude, but, since $\partial u/\partial x$ was usually negative, they may be somewhat too large.

In order to change (10–12) into a form which is suitable for computation, it is desirable to insert p, defined

[5] Rossby and Montgomery (1935, p. 6) have shown that (5) holds for eddy viscosity under conditions of neutral equilibrium. For the purposes of this paper, the significant point is only that K is proportional to z. It will be necessary to know only the order of magnitude of the proportionality factor, for which purposes (5) may be expected to be adequate. Strictly speaking, K at the surface has a small finite value which may be neglected here.

by (1), in place of q, and to approximate the derivative $\partial p/\partial x$ by means of finite differences. The equations become

$$\frac{E}{(q_0 - q_1)} = -\frac{\bar{u}\bar{\rho}}{(x_2 - x_1)} \int_0^z (p_2 - p_1)\, dz, \quad (14)$$

$$G_b = \frac{1}{(p_0 - p_b)(x_2 - x_1)} \int_0^z (p_2 - p_1)\, dz, \quad (15)$$

$$K_z = -\frac{\bar{u}}{(\partial p/\partial z)_z (x_2 - x_1)} \int_z^z (p_2 - p_1)\, dz. \quad (16)$$

The symbol $\bar{u}$ represents an effective mean wind speed, which can be approximated from the observed wind force at the sea surface; in (15) it has been assumed to be the same as u_b. The subscripts 1 and 2 refer to soundings made at two distances from shore.

Fig. 3 illustrates the method of evaluating the integrals in (14–16). In practice the variation of p_2 and

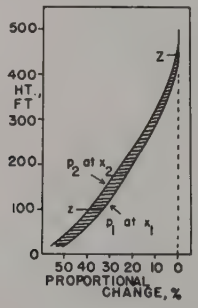

FIG. 3. The curves p_1 and p_2 represent distributions of proportional change at distances x_1 and x_2. The shaded area above any height z represents $\int_z^z (p_2 - p_1)dz$.

p_1 with z above 20 ft is known from actual soundings. The contribution of the region below 20 ft to the integrals in (14, 15) has been neglected. The term $(\partial p/\partial z)_z$ in (16) has been estimated by drawing tangents to the soundings at z and averaging the values obtained at x_1 and x_2.

The results obtained from calculations based on (14–16), are shown in table 2. In (15), the level b was taken as 20 ft, the height of the lowest available observation. In some cases computations were based on the mean of two or more soundings at nearly the same distance from shore. The most doubtful of the values presented are those of eddy diffusivity near the tops of soundings, where the vertical gradient of humidity or potential temperature was small, or in the interval nearest land, where the vertical gradient was changing rapidly.

For group I (stability small and wind appreciable), the eddy diffusivity appears to increase upward as far as 200–250 ft and then to decrease rapidly with height.

TABLE 2. Values of eddy diffusivity (K, in 10^3 cm^2 sec^{-1}), relative evaporation ($E/(q_0 - q_i)$ in 10^{-4} g cm^{-2} sec^{-1}), and of the nondimensional parameter $10^3 G_b$ referred to a level of 20 ft.

	Group I. ΔT = 4.2F, u_{1000} = 26 mi hr^{-1}		
	0–9 mi	9–25 mi	25–45 mi
K at z = 700 ft	—	—	1.2
650	—	—	3.2
600	—	—	6.3
550	—	0.53	2.9
500	0.34	1.9	4.4
440	2.6	5.3	6.9
400	6.9	10.2	9.8
350	13.8	15.2	12.8
300	37.8	26.6	17.7
250	55.0	30.0	20.5
200	56.3	25.9	24.0
150	49.0	13.7	17.3
100	37.5	8.4	14.4
50	16.1	2.7	7.0
$E/(q_0 - q_i)$	12.64	2.66	1.46
$10^3 G_b$	1.96	0.54	0.68
	Group II. ΔT = 6.5F, u_{1000} = 15 mi hr^{-1}		
	0–3 mi	3–13 mi	13–25 mi
K at z = 300 ft	—	—	1.5
250	—	0.52	1.5
200	—	1.5	1.7
150	—	3.2	1.8
100	—	5.6	1.9
50	0.61	4.5	1.9
$E/(q_0 - q_i)$	1.66	4.38	2.06
$10^3 G_b$	0.33	1.08	0.67
	Group III. ΔT = 7.5F, u_{1000} = 22 mi hr^{-1}		
	0–2½ mi	2½–10 mi	10–26 mi
K at z = 400 ft	—	—	1.2
350	—	—	2.3
300	—	—	3.6
250	—	—	6.0
200	—	0.57	3.4
150	1.2	1.1	2.9
100	2.4	0.90	2.4
50	6.3	0.81	1.6
$E/(q_0 - q_i)$	8.78	1.16	2.14
$10^3 G_b$	1.90	0.31	0.65

The largest values found are of the order of 50×10^3 cm^2 sec^{-1}. The values for this group are the ones which can best be compared with values for neutral equilibrium found by other investigators. Schmidt (1925), considering the vertical distribution of the phase of the temperature period observed on the Eiffel Tower and assuming K to be independent of height within various layers, has computed mean values of 8×10^3, 12×10^3, and 9×10^3 cm^2 sec^{-1} for the layers 2–123 m, 123–197 m, and 197–302 m respectively. Mildner (1932), from pilot-balloon observations, determined the vertical distribution of eddy viscosity, which for neutral equilibrium is comparable with eddy diffusivity. For his data, the eddy viscosity increased approximately linearly upward to a maximum of about 400×10^3 cm^2 sec^{-1} at a height of about 700 ft and then decreased rapidly above. Sverdrup (1933) also found the linear increase up to a certain height. Rossby (1932) from theoretical considerations has found that the eddy viscosity increases linearly with height up to a certain level and then decreases as the square of the

TABLE 2.—*Continued*

	0–2 mi	2–8½ mi	8½–16 mi	16–23½ mi
Group IV. ΔT = 9.9F, u_{1000} = 23 mi hr^{-1}				
K at z = 250 ft	—	0.79	0.17	0.34
200	—	2.8	0.81	0.71
150	3.2	2.4	1.6	1.0
100	8.6	2.3	2.7	1.3
50	15	2.0	2.9	1.2
$E/(q_0 - q_i)$	5.56	2.26	4.48	1.74
$10^3 G_b$	1.10	0.52	1.33	0.67

	0–2 mi	2½–9 mi	9–30 mi
Group V. ΔT = 10.0F, u_{1000} = 14 mi hr^{-1}			
K at z = 150 ft	—	0.48	0.021
100	—	1.1	0.068
50	0.26	0.92	0.12
$E/(q_0 - q_i)$	3.04	1.64	0.44
$10^3 G_b$	1.15	0.80	0.26

	0–2 mi	2–9½ mi	9½–23 mi
Group VI. ΔT = 12.4F, u_{1000} = 35 mi hr^{-1}			
K at z = 250 ft	—	—	0.84
200	—	—	2.7
150	—	0.58	2.0
100	1.6	1.4	2.4
50	6.4	1.6	2.0
$E/(q_0 - q_i)$	10.64	2.90	2.98
$10^3 G_b$	1.48	0.53	0.61

	0–2½ mi
Group VII. ΔT = 18.0F, u_{1000} = 18 mi hr^{-1}	
K at z = 50 ft	0.83
$E/(q_0 - q_i)$	2.40
$10^3 G_b$	0.86

height. Thus, the deductions from group I are compatible with all these investigations.

In the other groups, no such clear-cut variation with height is apparent. Rather, the eddy diffusivity appears to be more or less independent of height in the region between 50 ft and the upper levels of computation, especially if the doubtful values obtained near the top are disregarded. Moreover, there is no clear variation with distance from shore. The order of magnitude of the eddy diffusivities obtained is 10^3 cm^2 sec^{-1}. Because of the stability of the air measured by the soundings in these groups, the values are comparable to some results obtained by Taylor (1914; 1915). From seven kite soundings made aboard the whaling ship "Scotia" over the Grand Banks of Newfoundland, Taylor, assuming the eddy diffusivity to be independent of height, found values between 1×10^3 and 3×10^3 cm^2 sec^{-1}. These compare well with the values found here.

No direct determinations of G_b other than those of the present investigation are known to the writer. However, it has been pointed out that G_b may be expected to be approximately the same as the product $\kappa\gamma_b\Gamma_b$, and the value of each of these factors is known within rather wide limits. Montgomery (1940) and Sverdrup (1946) found values of Γ lying between 0.04 and 0.18. Montgomery (1943) found κ to be 0.45 and discussed other determinations which yield values near 0.40. The resistance coefficient, γ, may lie between 0.02 and 0.05 (Rossby, 1936, fig. 1 and pp. 12–13). Accordingly, from the upper and lower limits quoted for Γ, κ, and γ, it may be expected that

$$0.3 \times 10^{-3} < G_b < 4 \times 10^{-3}.$$

The values shown in table 2 fall within this range, lying nearer the lower limit than the upper one.

5. A theoretical model

In this section a simple model for the distribution of eddy diffusivity in the stable air represented by the modification cross sections will be proposed and tested. This model is based in part on the results of previous investigations which lead to the conclusion, as discussed in section 3, that the eddy diffusivity increases linearly with height in the lowest few meters above the sea surface. It is also based on the numerical results of the present investigation, as given in section 4, which indicate that, except for group I, the eddy diffusivity in air passing over cooler water is essentially independent of height above the sea surface and distance from land, for given conditions of temperature excess and wind speed and within limits of height and distance encompassed by the observations. The distributions of temperature and humidity to be expected on the basis of this scheme will be computed and compared with the original soundings.

In this model, the eddy diffusivity increases linearly from a value of zero at the surface to a value of K_H at the height H and has the value K_H at all levels above H. The parameters K_H and H are assumed to be constant with distance from land, but they vary with temperature excess and wind speed from group to group. The model is not applicable to group I, for which the distribution of eddy diffusivity appears to be similar to the expected distribution for conditions of neutral equilibrium.

From (8), if vertical motion and the variation of density with elevation are neglected and if the proportional change is used,

$$u\frac{\partial p}{\partial x} = \frac{\partial}{\partial z}\left(K\frac{\partial p}{\partial z}\right). \tag{17}$$

In the surface layer, where K increases linearly with height, an equation results similar to one for which Haurwitz (1936) has found a solution in terms of Bessel functions. A formal solution for the lower layer is, however, unnecesary. The vertical distribution of proportional change must be very nearly logarithmic, as was pointed out in section 3, and the layer turns out to be so shallow that any small departures from this

distribution are not of interest. This lower layer is, nevertheless, of fundamental importance because it furnishes a boundary condition for the solution for the air above H.

From (4), if the reference level is taken as H and the proportional change is used,

$$\Gamma_H = \frac{H}{1 - p_H}\left(\frac{\partial p}{\partial z}\right)_H. \tag{18}$$

In view of (5) and (7) this may be written as

$$\frac{G_H}{L}(1 - p_H) = -\left(\frac{\partial p}{\partial z}\right)_H, \tag{19}$$

where $L \equiv K_H/u_H$ has the dimensions of length. Since the level H is a boundary between the lower layer of increasing eddy diffusivity and the upper layer of constant eddy diffusivity, (19) serves as a boundary condition for the solution for the upper layer.

For the stable air above H, (17) becomes

$$\frac{\partial p}{\partial x} = L\frac{\partial^2 p}{\partial z^2}. \tag{20}$$

In addition to the relation stated in (19), boundary conditions are $p = 0$ at $x = 0$, $p \to 0$ as z increases, and $p \to 1$ as x increases. The solution of (20) which satisfies these conditions is

$$p = 1 - P\left(\frac{z - H}{2L^{\frac{1}{2}}x^{\frac{1}{2}}}\right) - \left\{\exp\left[\frac{G_H}{L}(z - H + G_H x)\right]\right\} \times \left\{1 - P\left(\frac{z - H + 2G_H x}{2L^{\frac{1}{2}}x^{\frac{1}{2}}}\right)\right\}. \tag{21}$$

Here P is the function

$$P(\alpha) = \frac{2}{\pi^{\frac{1}{2}}}\int_0^\alpha \exp(-\varphi^2)\, d\varphi,$$

which is often called the probability integral or error function, and which has been extensively tabulated, for example by Peirce (1929). The error function is 0 for $\alpha = 0$ and approaches 1 as α approaches ∞.

As x or z becomes very large, (21) may be written in the approximate form

$$p \approx 1 - P\left(\frac{z - H}{2L^{\frac{1}{2}}x^{\frac{1}{2}}}\right) - \frac{2\pi^{-\frac{1}{2}}L^{\frac{1}{2}}x^{\frac{1}{2}}}{z - H + 2G_H x} \times \exp\left[-\frac{(z - H)^2}{4Lx}\right], \tag{22}$$

which results from an expansion of $P(\alpha)$ for large values of α (Peirce, 1929, p. 120).

Equation (21) may be used to compute the value of the proportional change at any height z or distance from shore x, providing the constants G_H, L, and H are known. Appropriate values of the first two of these constants can be derived for each cross section directly from the numerical results of section 4. The values of H do not follow directly from the observations, but can be deduced with sufficient accuracy from (5). The computations to be made with the aid of (21) correspond to the conditions represented by each of the soundings in each of the groups (with the exception of group I). The procedures used to evaluate the constants G_H, L, and H for each cross section are discussed in turn below.

Values of the parameter G, referred to a height of 20 ft, are given in table 2 for each group at varying distances from shore. In (21), G_H is referred to the level H above which the eddy diffusivity is constant. Since the position of this level cannot be determined from the observations alone, the values of G given in table 2 are assumed to apply for G_H. Probably no great error is introduced by this procedure. For each cross section, the values of G at the various distances from shore are averaged to give a mean value which is used for all soundings in the cross section.

The parameter L is defined as the ratio, K_H/u_H, of the constant value of eddy diffusivity above H to the wind speed at H. Values of K are given in table 2. Mean values of K are determined for each cross section by averaging nearly all the values of K appropriate to the cross section. The few doubtful values discarded in this procedure are those in the region nearest shore and those near the top of the stable air in other regions. For values of u_H, the only available observations are those of wind force at the surface. For each cross section, the average wind force, as shown in table 1, is used. The wind speeds are then derived according to the approximate relationships: Beaufort force 2 corresponds to a wind speed of 6 mph, force 3 to 10 mph, force 4 to 15 mph. These are consistent with the standard meteorological relationships. Average values of L for each cross section follow from the average values of K_H and u_H.

The values of H for each cross section cannot be determined from the results of this investigation alone. However, H enters (21) only as a subtractive correction to the vertical coordinate z, because z refers to distance above the sea surface whereas the lower boundary is actually at $z = H$. Because the values of eddy diffusivity above 50 ft given in table 2 are essentially independent of height, H is less than 50 ft and is less than the values of z for which computations are made. Accordingly, H needs to be known only approximately, and errors in its determination can result only in a shift of the vertical scale for the computed soundings. For this purpose, it is perfectly satisfactory to

assume that (5) applies to the linear increase of eddy diffusivity in the lowest layer and to compute H for each cross section, using the appropriate values of K_H and u_H, determined as described in the previous paragraph, and an appropriate value of $\kappa\gamma_H$ inferred from other investigations. Here, $\kappa\gamma_H = 2 \times 10^{-2}$ has been used.

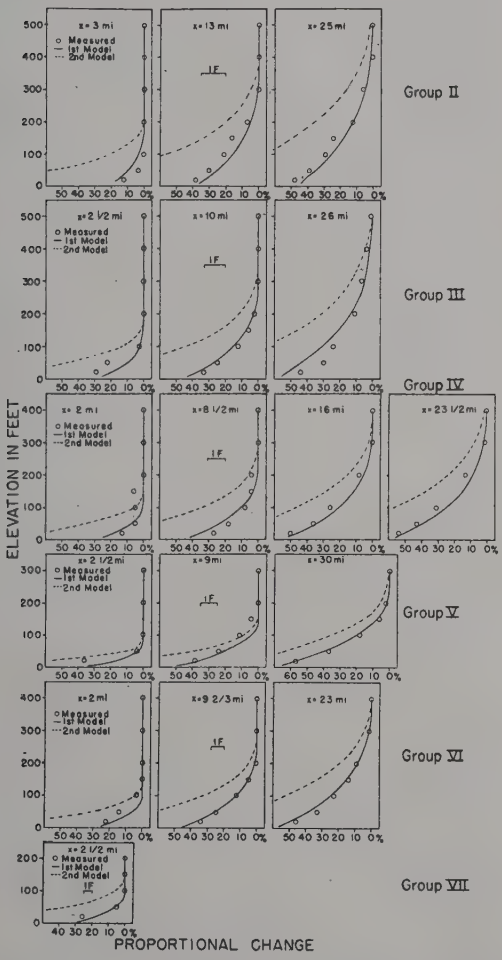

FIG. 4. Measured values and computed distributions of proportional change. Computations for the first model are made with the use of (21), those for the second model are made with the use of (23). In the following cases, the "measured" values are actually averages based on two or more soundings made at nearly the same distance from shore: Group III, $x = 26$ mi, averages based on soundings at $x = 24$ mi and $x = 28$ mi; group IV, $x = 8\frac{1}{2}$ mi, averages based on soundings at $x = 8$ mi and $x = 9$ mi; group IV, $x = 16$ mi, averages based on soundings at $x = 14$ mi and $x = 18$ mi; group IV, $x = 23\frac{1}{2}$ mi, averages based on soundings at $x = 21$ mi and $x = 26$ mi; group V, $x = 9$ mi, averages based on soundings at $x = 8$ mi and $x = 10$ mi; group V, $x = 30$ mi, averages based on soundings at $x = 24$ mi, $x = 30$ mi, and $x = 36$ mi; group VI, $x = 9\frac{2}{3}$ mi, averages based on soundings at $x = 8$ mi, $x = 9$ mi, and $x = 12$ mi; group VII, $x = 2\frac{1}{2}$ mi, averages based on soundings at $x = 2$ mi and $x = 3$ mi.

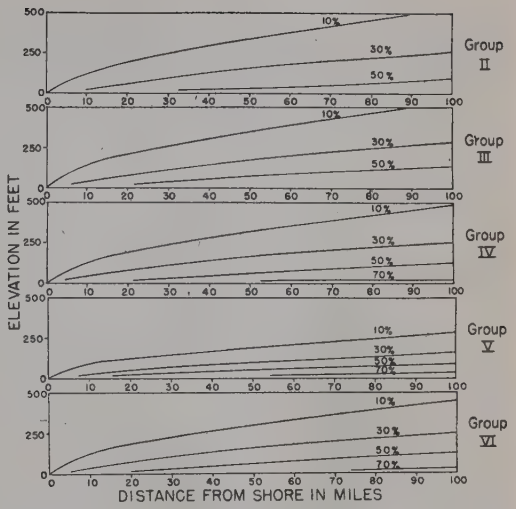

FIG. 5. Theoretical modification cross sections computed with the aid of (21). The stability and wind conditions correspond to those represented in the empirical cross sections (fig. 2).

Thus, fixed values of L, G_H, and H are estimated for each group except group I and used in conjunction with (21) to compute soundings corresponding to those shown on the cross sections. Table 3 gives the values

TABLE 3. Values of parameters used in computing soundings by means of equation (21).

Group	K_H cm² sec⁻¹	u mi hr⁻¹	L cm	G_H	H m
II	2.2×10^3	10	4.9	0.69×10^{-3}	2.5
III	1.9	10	4.2	0.92	2.1
IV	1.5	10	3.4	0.92	1.7
V	0.3	6	1.0	0.71	0.5
VI	1.9	15	2.8	0.87	1.4
VII	0.7	6	2.6	0.86	1.3

of the parameters used for each group. The values listed for group VII are strictly not comparable with others, since only two soundings were available, both very near shore.

In fig. 4 the observed soundings and those computed from (21) are shown. As an aid to judging the success of (21) as a representation of the observations, computations based on a second model, which is discussed in the next section, are included in fig. 4.

As a further means of showing the results of (21) graphically, theoretical modification cross sections corresponding to groups II–VI have been computed and are presented in fig. 5. The sections extend from shore to a distance 100 miles off shore because they are intended to reveal the nature of the model; that the model correctly represents natural conditions beyond the extent of the observations would be an unwarranted conclusion. Later Radiation Laboratory airplane soundings, similar to those used in this study but

at distances of the order of 100 miles from shore, have been presented and discussed by Emmons (1947). These show very clearly that under actual conditions the effects of radiation, shear, and variations in water temperature become increasingly important with distance from shore.

6. Taylor's model and its application to the observations

A different assumption has been made previously in connection with turbulence problems (Taylor, 1915; Haurwitz, 1941, p. 228), namely that the eddy diffusivity is constant with the value K_H all the way down to the sea surface. The solution for this case is given by an expression very similar to the first two terms of (21),

$$p = 1 - P\left[\frac{z}{2L^{\frac{1}{3}}x^{\frac{1}{3}}}\right]. \tag{23}$$

The results of computations based on this assumption are shown in fig. 4.

It is evident from fig. 4 that (21) is a satisfactory functional representation of the data. Equation (23), on the other hand, is quite inadequate. Both equations are consistent with the qualitative conclusions from the data, namely, that the eddy diffusivity is approximately constant above 50 ft and at all distances from shore; (21), however, takes into account the existence of a boundary layer in the lowest meter or two in which the eddy diffusivity increases linearly with height.

Taylor's (1915) determination of the order of magnitude of the eddy diffusivity in stable air agreed with the order of magnitude obtained here, but was based on an expression equivalent to (23). His method was simply to determine the height at which $p = 0.5$ from his soundings and to solve (23) for L, and hence K, in terms of this height. The application of his method to the data presented here would, however, yield values of eddy diffusivity of the order of magnitude of 10^2 cm^2 sec^{-1}, a tenth of the present values. For example, in the case of the sounding at $x = 26$ mi in group III, Taylor's method would give $K = 0.09 \times 10^3$ cm^2 sec^{-1} compared with 1.9×10^3 cm^2 sec^{-1} derived here. The latter value must be considered the more nearly correct one, in view of the marked success of the present model in representing the data.

Taylor, however, was concerned with soundings at distances of a few hundred miles from shore. At these distances, the method of section 4 and Taylor's method based on (23) should be expected to yield approximately the same value of K. Indeed, it can be shown that, in the case of group III, for example, the value of eddy diffusivity derived from (23) would differ from that derived on the basis of (21) by less than 10 per cent for $x > 450$ mi. Hence Taylor was entirely justified in his work, but his method should not be applied to soundings near shore.

7. Summary and conclusions

The modification cross sections (fig. 2) involve no restrictive assumptions, but are merely a convenient way of presenting the observations. It must be remembered, however, that the data included in these cross sections have been carefully selected so that they represent the simplest possible meteorological conditions. Most actual cases of air moving over cooler water are complicated by such factors as initial stability in the air column before leaving land, variability of water temperature, radiational cooling of the air, or wind shear.

Despite these reservations, certain general conclusions which follow from the cross sections have been shown by other Radiation Laboratory soundings to be valid in nearly all actual cases. First of all, the height to which the air is appreciably cooled and moistened (or dried) during its first fifty miles over the water is of the order of magnitude of only a few hundred feet. Second, it is quite clear that this height of noticeable modification increases rapidly within the first few miles from shore and tends to level off thereafter. The third principal conclusion is that the amount and type of modification depends significantly on the stability, as represented by the temperature difference between air and water, and on the wind speed. The relative influence of these two factors is difficult to determine. However, group I, with small temperature excess and appreciable wind, and group V, with larger excess and light wind, are significantly different from the other groups. On the other hand, the other groups, representing a large variety of conditions, do not differ widely among themselves.

The eddy diffusivity at heights from 50 ft up to the top of the stable layer has been computed from the two-dimensional distributions represented on the cross sections, the necessary assumptions being that the vertical velocity component is zero and that normal to the sections there is no variation of temperature, humidity, or velocity. The effects thus neglected, although significant, are relatively minor and do not affect the order of magnitude of the computed eddy diffusivity. The resulting values, 1×10^3 to 50×10^3 cm^2 sec^{-1}, do not depend on the common assumption that eddy diffusivity is either vertically constant or varies with height in a given manner, and they are probably the most reliable that have been determined for air over the ocean.

In each group except group I, the values of eddy diffusivity appear to be constant with both x and z within the degree of uncertainty involved in their determination. In line with this result, a model was set

up in which eddy diffusivity is assumed to be independent of x but to increase linearly with z, in agreement with well established boundary-layer relationships, from zero in the laminar layer at the sea surface to K_H at the height H and to be constant with the value K_H everywhere above H. The values of H are about 1 m. The proportional-change distributions according to this model (figs. 4, 5) have been computed for comparison with the observed distributions. Although the model is a very incomplete representation of the natural processes, it enables the observed distributions to be reproduced to a first approximation, which is not achieved by either constant or linearly increasing eddy diffusivity throughout the entire stable layer.

Acknowledgments.—The observations used in this paper were made possible only through the combined efforts of all members of Group 42, Radiation Laboratory. The meteorological analysis of the data, which resulted in the selection of the particular soundings used here, was directed by Dr. R. B. Montgomery, who was aided by Mr. I. Katz, Mr. P. J. Harney, and the author. The actual preparation of this paper was undertaken at the suggestion of Dr. Montgomery, who has aided immeasurably in bringing it to its final form.

REFERENCES

Craig, R. A., I. Katz, P. J. Harney, 1945: Sea-breeze cross sections from psychrometric measurements. *Bull. Amer. meteor. Soc.*, **26**, 405–410.

Craig, R. A., 1946: Measurements of temperature and humidity in the lowest 1000 feet of the atmosphere over Massachusetts Bay. *Pap. phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole ocean Instn.*, **10**, no. 1, 48 pp.

——, 1947: Observations of vertical temperature and humidity distributions in the convective layer above the sea surface. *Ann. N. Y. Acad. Sci.*, **48**, 783–788.

Emmons, G., 1947: Vertical distributions of temperature and humidity over the ocean between Nantucket and New Jersey. *Pap. phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole ocean. Instn.*, **10**, no. 3, 89 pp.

Goldstein, S., Editor, 1938: *Modern developments in fluid mechanics.* Oxford University Press, 2 vols., 702 pp.

Haurwitz, B., 1936: The daily temperature period for a linear variation of the Austausch coefficient. *Trans. roy. Soc. Canada*, Third Series, Section III, **30**, 1–8.

——, 1941: *Dynamic meteorology.* New York, McGraw-Hill Book Co., 365 pp.

Katz. I., 1947: An airplane psychrograph. *Bull. Amer. meteor. Soc.*, **28**, 363–370.

Kerr, D. E., and others, 1949(?): *Propagation of short radio waves*, New York, McGraw-Hill Book Co., *Radiation Laboratory Series*, **13**, to be published.

Lettau, H., 1939: *Atmosphärische Turbulenz*, Leipzig, Akademische Verlagsges., 283 pp. (Reprint, Ann Arbor, Edwards Brothers, 1944.)

Mildner, P., 1932: Über die Reibung einer speziellen Luftmasse in dem untersten Schichte der Atmosphäre. *Beitr. Physik fr. Atmos.*, **19**, 151–159.

Montgomery, R. B., 1940: Observations of vertical humidity distribution above the ocean surface and their relation to evaporation. *Pap. phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole ocean. Inst.*, **7**, no. 4, 30 pp.

——, 1943: Generalization for cylinders of Prandtl's linear assumption for mixing length. *Ann. N. Y. Acad. Sci.*, **44**, 89–103.

——, 1947: Over-water refraction of 10-cm electromagnetic radiation, *Bull. Amer. meteor. Soc.*, **28**, 1–8.

Peirce, B. O., 1929: *A short table of integrals*, 3rd ed. Boston, Ginn and Co., 156 pp.

Rossby, C. G., 1932: A generalization of the theory of the mixing length with applications to atmospheric and oceanic turbulence. *Mass. Inst. Tech. meteor. Pap.*, **1**, no. 4, 36 pp.

——, and R. B. Montgomery, 1935: The layer of frictional influence in wind and ocean currents. *Pap. phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole ocean. Instn.*, **3**, no. 3, 101 pp.

——, 1936: On the frictional force between air and water and on the occurence of a laminar boundary layer next to the surface of the sea. *Pap. phys. Ocean. Meteor., Mass. Inst. Tech. and Woods Hole ocean. Instn.*, **4**, no. 3, pp. 3–20.

Schmidt, W., 1925: *Der Massenaustausch in freier Luft und verwandte Erscheinungen.* Hamburg, Verlag von Henri Grand, 118 pp.

Sheppard, P. A., 1946: Radio meteorology: influence of the atmosphere on the propagation of ultra-short radio waves. *Nature*, **157**, 860–862.

Sverdrup, H. U., 1933: Norwegian North Polar expedition with the "Maud," 1918–1925, **2**, Part 1.

——, 1936: The eddy conductivity of the air over a smooth snow field. *Geofys. Publ.*, **11**, No. 7.

——, 1938: On the influence of stability and instability on the wind profile and the eddy conductivity near the ground. New York, Wiley and Sons, *Proc. of the Fifth Intern. Cong. for App. Mech.*, 369–372.

——, 1946: The humidity gradient over the sea surface. *J. Meteor.*, **3**, 1–8.

Taylor, G. I., 1914: Report by Mr. G. I. Taylor. London, Darling and Son, *Ice observation, meteorology and oceanography in the North Atlantic Ocean, Report on the work carried out by the S. S. "Scotia,"* 1913, pp. 48–68.

——, 1915: On eddy motion in the atmosphere. *Phil. Trans. roy. Soc.(A)*, **215**, 1–26.

Contribution No. 469

TRAJECTORIES OF SMALL BODIES SINKING SLOWLY THROUGH CONVECTION CELLS[1]

By

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INTRODUCTION

Mr. J. C. Neess of the University of Wisconsin has indicated to the writer in a personal communication that he has often observed a greater variability in plankton tows taken up or down wind in a lake than when made across wind. He suggested that this might be due to convective or wind-induced cellular motion in the water, which in some manner should act to concentrate plankton in linear arrays in the direction of the wind, thus leaving relatively clear lanes between. This fact suggested that it might be of interest to set up a simple cell analytically and to see what kinds of paths or trajectories the particles of various settling velocities would describe.

The existence of long strip wind-induced cellular motion in lakes and oceans has been demonstrated (Langmuir, 1938; Woodcock, 1941). The nature of the trajectories should not depend necessarily on the nature of the forces producing the cellular motion, so that the results should apply equally well to thermally-induced cellular motion. The layer of wind-induced or thermally-induced strip cells may be thought of in the following way. The layer is divided into a number of strips (or cells) lying side by side with their lengths parallel to the wind. The water in each cell is rotating around the central axis of each cell, the sense of rotation in any given cell being opposite to that of its immediate neighbors, much like the rotation of a long train of gears. The boundaries of these cells are regions of sinking and rising water alternately. In addition to the rotating movement there is a movement in the direction of the wind so that a given particle of water describes a helix with axis horizontal and in the direction of the wind.

Fig. 1 shows a cross section view of two neighboring cells. The arrows indicate the direction of water movement in the plane perpendicular to the wind direction; the curved lines are streamlines. The motion of the water in the direction of the wind clearly has no effect

[1] Contribution No. 469 from the Woods Hole Oceanographic Institution.

[2] The writer wishes to thank Dr. C.-G. Rossby for reading this paper and suggesting several important improvements.

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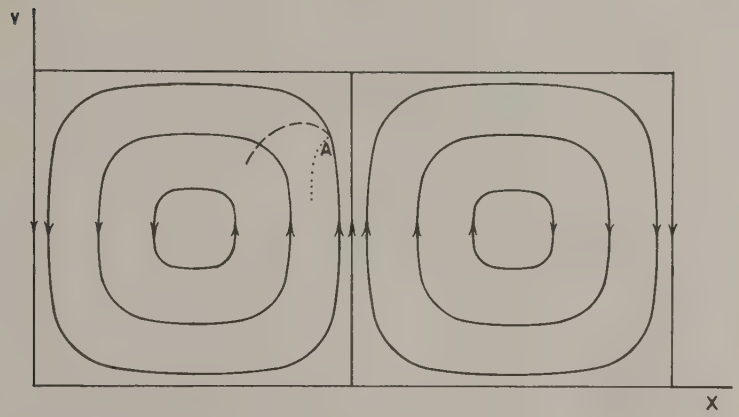

Figure 1. The streamlines of an idealized vertical section across a pair of convection cells. The arrows show the direction of the water flow.

upon the trajectory of a particle immersed in the cell except to move it uniformly in the direction of the wind. We may consider the problem as essentially two dimensional.

A small body whose density is the same as that of the water will have no tendency to settle. Therefore its trajectory will lie along the streamlines of Fig. 1—in other words it will simply move along with the water. Particles whose densities are greater than that of the water will tend to sink with a constant settling velocity, and if placed in still water they will tend to settle vertically downward in straight line trajectories. In case of convective motion, as shown in Fig. 1, such a heavy particle introduced at point A cannot rise along the streamline as would a particle with zero settling velocity; rather, it will start to fall immediately (for example, along the dotted line), and, if heavy enough, will fall through the bottom of the convective layer. A particle with a smaller settling velocity, if placed initially at point A, will begin to rise at first because the rising current is strong there, but eventually it will be swept horizontally to a region where the upward velocity is less and hence it will fall away (for example, along the dashed line).

One naturally wonders if this particle will be caught up again into the ascending current and so execute an endless number of circuits, or whether it is bound eventually to fall out of the layer. As a matter of fact, one begins to wonder whether all particles with a settling velocity—no matter how small—will eventuallly fall out of the con-

vective layer. This is not the case, however, as will be shown in the following section.

THEORETICAL TREATMENT

A system of axes is fixed to the layer as shown in Fig. 1. The coordinates of a particle are (x, y), both of which are functions of the time t; $x(t)$, $y(t)$.

The horizontal velocity of the particle is dx/dt, the vertical velocity dy/dt. The fluid motion may be specified by a stream function ψ, which, in general, is quite arbitrary. The horizontal and vertical velocities of the water are $\partial\psi/\partial y$ and $-\partial\psi/\partial x$ respectively.

If the settling velocity is denoted by V, we know that

$$\frac{dx}{dt} = \frac{\partial\psi}{\partial y}; \frac{\partial y}{\partial t} = -\frac{\partial\psi}{\partial x} - V.$$

The trajectories may be specified by a function ψ_1 where

$$\frac{dx}{dt} = \frac{\partial\psi_1}{\partial y}; \frac{dy}{dt} = -\frac{\partial\psi_1}{\partial x}.$$

The function ψ_1 is therefore given by the following expression

$$\psi_1 = \psi + Vx.$$

The trajectory of a particle is a curve along which ψ_1 is constant. The result is quite general. In the case of convection cells the simplest stream function to consider is

$$\psi = \psi_0 \sin x \sin y.$$

The streamlines of Fig. 1 were constructed from this function.

In this case the trajectories are given by

$$\frac{\psi_1}{\psi_0} = \sin x \sin y + Rx,$$

where the quantity R is defined by

$$R = V/\psi_0.$$

The trajectories shown in Figs. 2, 3, and 4 were constructed from this function.

DISCUSSION OF RESULTS

It is convenient to discuss the trajectories for different settling velocities in terms of the quantity R: the ratio of the settling velocity to the maximum upward water velocity.

The case where $R \geqslant 1$. If R is quite large the trajectories are essentially straight vertical lines. As R approaches unity the trajectories become curved. Fig. 2 is drawn for the limiting case $R = 1$. The particles all settle out, but as they approach the region of maximum upward motion they diverge and fall more slowly, as if to avoid that region.

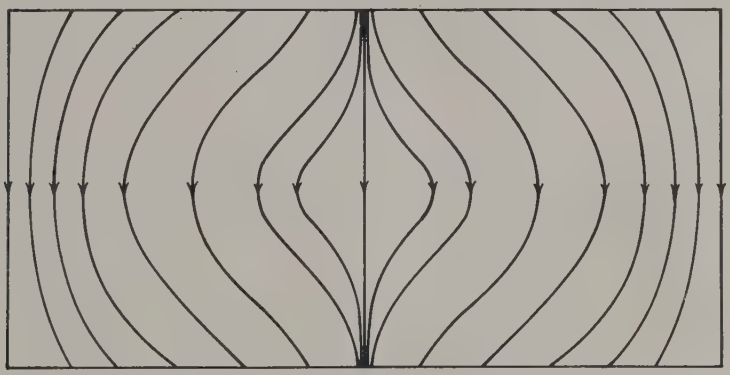

Figure 2. The trajectories of small bodies whose sinking velocity is just sufficient to insure that they all settle out.

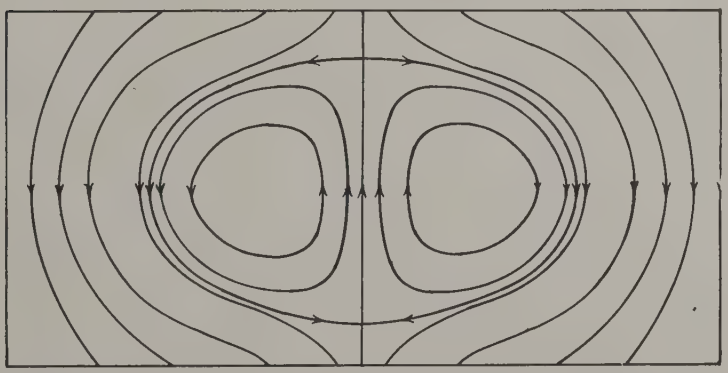

Figure 3. The trajectories of small bodies whose sinking velocity is just one-half of those in Fig. 2. The closed trajectories lie within a region conveniently called the region of retention.

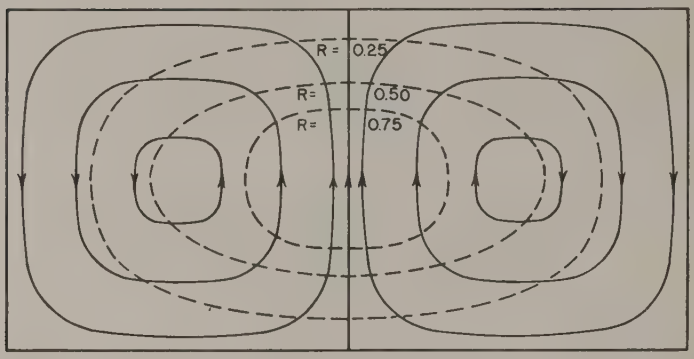

Figure 4. Solid lines are streamlines of the convective motion as shown in Fig. 1. Dashed lines are the boundaries of the regions of retention for various values of the number R.

The case where $1 > R > 0$: There are regions of the fluid motion where the particles, though constantly falling relative to the water, are moved upward through the convective layer. Fig. 3 is drawn for the case $R = 0.5$. The interesting feature of this figure is that there are closed trajectories in the upward current. A particle placed on one of these trajectories makes an endless number of circuits and does not fall out of the convective layer despite the fact that it is always falling relative to the fluid. The trajectories more remote from the region of maximum upward velocity are not closed. Particles placed on one of these trajectories fall out of the convective layer.

If particles are strewn at random into the cell, shown in Fig. 4, some will fall out while others are retained in closed circuits. After awhile two distinctly different regions in the fluid will be clearly visible: (i) a region which has lost all of its particles and (ii) a region of closed trajectories which has retained its particles in closed trajectories. The latter region may be spoken of as the "region of retention."

The region of retention becomes larger as R approaches zero. The boundaries of the regions of retention for values of R, equal to 0.25, 0.50, and 0.75, are shown in Fig. 4.

If particles of different settling velocities are introduced simultaneously, a sorting process ensues, in which heavier ones are concentrated near to the upward water currents and lighter ones extend to greater distances from the upward currents.

The population density of particles of a given R will be zero outside the region of retention, but it will not be uniform within that region.

Near the upward currents the space velocity of the particles is smaller than in other portions of the retention region, and therefore, from the principle of continuity, the density of population will be greater in the center of the regions of retention.

In actual convection cells there is always some degree of turbulence present, so that there will always be some turbulent exchange across trajectories of particles. In such a case a region of retention must gradually lose its particles by turbulent exchange with the outside region, the rate of loss depending upon the degree of turbulence.

If a sharp density increase occurs directly beneath the convective layer, particles that have a settling velocity in the convective layer will not necessarily sink through the underlying water. In nonturbulent cellular convection this would mean that there was an accumulation along the x-axis (Fig. 1) of those particles which were not in the region of retention, the accumulation being particularly dense on the x-axis directly under the regions of retention. In the presence of turbulence there will be a slight turbulent exchange between this accumulation of particles on the bottom of the convective layer and those in the region of retention. On the whole, an equilibrium would be established with a certain fraction of the population in the region of retention, most of the remainder on the x-axis directly under the region of retention, and a very small fraction moving en route between these two centers of population through the "clear" region.

Particles less dense than water have an upward velocity relative to the water (e. g., pelagic sargassum, providing settling is independent of depth). They cannot escape through the free surface. It would be evident that the preceding discussion may be applied to this case by simply inverting the picture.

There is a possibility that the method here advanced might be applicable to problems in convective clouds.

REFERENCES

Langmuir, Irving

1938. Surface motion of water induced by wind. Science, *87* (2550): 119–123.

Woodcock, A. H.

1941. Surface cooling and streaming in shallow fresh and salt waters. J. Mar. Res., *4* (2): 153–161.

Contribution No. 470

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 19, NO. 2, PP. 71–77
FIG. 1, AUGUST 1949

SYNTHESIS OF SAND MIXTURES*

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ABSTRACT

A method is offered for synthesizing sand mixtures with a normal probability size-frequency distribution, and any desired mean and sorting. Tables and a graph permit rapid use of the method for certain phi standard deviations and for any phi mean diameter. Graphical and mathematical solutions are also presented so that any normal sand may be mixed.

NOTATION

C_s = coefficient of sorting
M = mean diameter
Md = median diameter
M_ϕ = phi mean diameter
$M_{\phi n}$ = nominal phi mean diameter
Q_1 = larger quartile
Q_3 = smaller quartile
$\phi = -\log_2 n$, where n is the grain size in millimeters. If $M\phi_1 = M\phi_2 + \phi$, then $M_1 = 2M_2$
σ_ϕ = phi standard deviation

INTRODUCTION

Sediments are analyzed every day but they are seldom synthesized. The author has mixed sands in order to measure the effect of sorting on the transportation of bed-load. Krumbein and Monk (1942) have mixed them previously to determine the influence of sorting on permeability. Some solutions to the problem of synthesizing a sand mixture with a natural size-frequency distribution and given characteristics are presented here. The general procedure employed is to sieve one or more natural sands in order to obtain a number of size fractions. These fractions may be combined in proportions determined by the graph and tables included in this paper to synthesize a sand.

The author is indebted to the Woods Hole Oceanographic Institution for a summer fellowship which made this study possible. Mr. Joseph Rominger and Mr. Henry C. Stetson have been kind enough to read the manuscript. Mr. Rominger has corrected several errors and pointed out the paper by Krumbein and Monk.

* Contribution No. 470 from The Woods Hole Oceanographic Institution.

SIZE-FREQUENCY DISTRIBUTIONS IN NATURAL SEDIMENTS

Many natural sediments have been found to have a size-frequency distribution which corresponds to normal probability. For this reason the sand mixtures produced by the methods suggested in this paper may be considered to be the same as natural ones. Moreover, Doeglas (1946) has demonstrated that apparantly abnormal distributions are nothing but remnants of normal ones from which the other parts have been removed by sedimentary processes. In the event that a skew distribution is desired, the present procedure may be modified in accordance with the data presented by Otto (1939).

THE PREDETERMINED PARAMETERS

There are any number of normal probability curves, but only one which has a certain mean and standard deviation (Krumbein, 1936). This is evident if it is remembered that the curve can be plotted as a straight line on probability paper, and that the mean and the standard deviation represent two points on that line. Therefore, it is necessary to consider only these two parameters if Krumbein's phi notation is to be used.

The coefficient of sorting and the me-

dian diameter also establish a unique probability curve. In fact the mean and the median are equal if the curve is normal (non-skew). Further, it may be demonstrated by use of tables for the solution of the normal probability curve, that the coefficient of sorting (C_s) is related to the phi standard deviation (σ_ϕ) as follows:

$$Q_1 - Q_3 = 1.349\sigma_\phi$$

and since $$C_s = \sqrt{\frac{Q_1}{Q_3}}$$

$$C_s = \sqrt{\frac{Q_3 + 1.349\sigma_\phi}{Q_3}}$$

$$= \sqrt{1 + \frac{1.349\sigma_\phi}{Q_3}}.$$

Krumbein (1939) has indicated the same relation by noting that the phi quartile deviation equals 0.6745 σ_ϕ. In short, either a sorting coefficient and median, or a standard deviation and mean will define a unique curve.

THE CURVE OF PROBABILITY

The equation of the "bell-shaped" probability curve has appeared in this journal at least twice (Krumbein 1938, Otto 1939), and extended discussion here would be pointless. The solution of the integral for the area under the curve is an infinite series. The solution for the area under a part of the curve, which is the exact equivalent of the weight per cent of a sample, may be obtained from tables in any text on statistics. One advantage of selecting the phi standard deviation instead of the coefficient of sorting as a parameter is that the former may be used directly in these tables whereas the latter requires some computation.

USE OF THE NOMINAL MEAN DIAMETER

A desired sediment may be synthesized by mixing together various weights of various grain sizes obtained by sieving a natural sediment. However, the pertinent grain size is the nominal phi mean diameter ($M_{\phi n}$) rather than the diameter of the sieve openings. The nominal phi mean diameter is equal to the sieve opening plus one half of the sieving interval. Its use results in a plot on probability paper which is symmetrical about the sieve size which contains the nominal mean of the whole sand mixture. By this device, the weight percentage of any grain size can be located directly below the size on the graph presented in this paper.

The nominal phi mean diameter is only an arithmetic approximation of the true phi mean diameter of the grains which are separated by a given sieve. In a natural sand, the true phi mean diameter of these grains will vary according to the normal probability distribution. It may be obtained from a probability graph by taking the average of the cumulative weight percentages of the subject sieve size and that of the next larger sieve. The diameter which corresponds to this average weight percentage for the given sorting is the true mean diameter. It may be calculated by the use of tables for the normal probability curve if the graph cannot be read to the desired accuracy.

The difference between some true and nominal phi mean diameters is shown in Figure 1. The sieve interval is one phi unit. It can be seen that for a given sieve size the difference increases as the standard deviation (or sorting coefficient) becomes smaller; and that for a given sorting the difference increases as the dispersion of the sieve size from the mean sieve size increases.

This difference introduces little error if the sand mixture to be synthesized has a size-frequency distribution similar to the natural sand from which the sand fractions are obtained. The error is negligible, regardless of the mean size, if both the sands have the same M_ϕ, if $\sigma_\phi \geq 2$, and if the sieve interval is no greater than one phi unit. This is shown in Figure 1 in that the true and nominal

mean diameters are almost equal within the range of standard deviations specified. The difference becomes important as the sorting improves. For example, it is impossible to produce a sand mixture with a normal probability distribution and a phi standard deviation of 0.5 by mixing size fractions derived from a natural sand with a $\sigma_\phi = 4.0$, and with the same mean. The relation can be seen in Figure 1 by considering the sand fraction which has a nominal M_ϕ larger by one phi unit than the M_ϕ of the whole sand. The fraction from the natural sand has a true mean diameter of about $M_\phi + \phi$, but the desired sand fraction has a true M_ϕ of about $M_\phi + 0.7\phi$. Thus various weight fractions of the natural sand may be mixed together according to the proportions for the desired sand, but the mixture so synthesized will not have a normal probability distribution.

There is a further complication because the mean of a natural sediment seldom coincides with the nominal mean diameter of the mean sieve. However, if the difference is no more than $\phi/10$, this error may be neglected. For fractions other than the mean one, this complication usually may be neglected regardless of the mean of the sand, provided the sieve interval is no greater than one phi unit. A comparison of lines (b) and (3) in Figure 1 shows this. The former line has a true M_ϕ which coincides with the nominal M_ϕ in the mean size fraction, however, for the latter one the true and the nominal M_ϕ differ by $\phi/2$. These two lines, therefore, represent the maximum possible range of differences be-

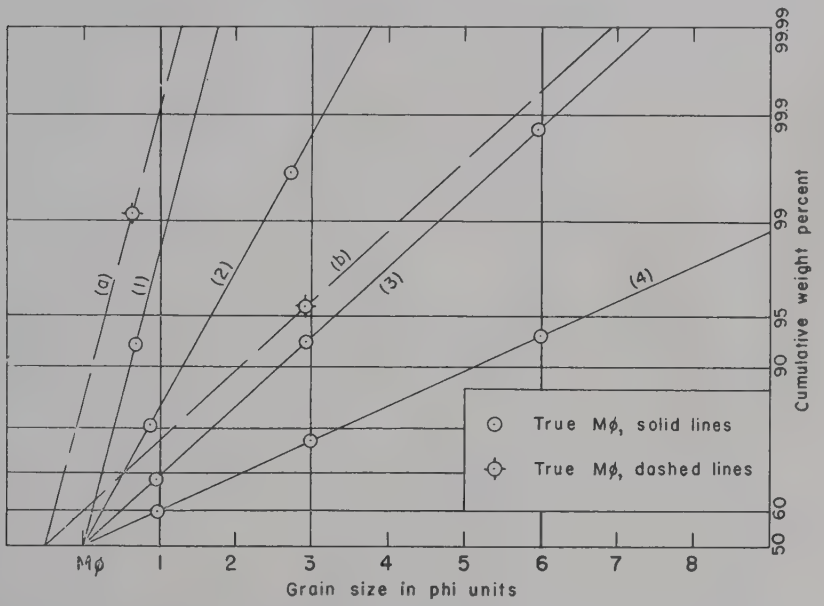

FIG. 1.—Variation between the true and nominal phi mean diameters. Size-frequency distributions are normal. Solid lines (1–4) indicate that the true and nominal phi mean diameters are equal in the mean size fraction; dashed lines (*a–b*) that the two differ by $\phi/2$ in the mean size fraction. Vertical lines through the grain diameter numbers show the nominal M_ϕ for that size fraction. The horizontal distance between the true and the nominal M_ϕ in any size fraction represents the variation in phi units.

tween true and nominal M_ϕ for a sieve interval of one phi unit. Nevertheless the true mean diameters of the lines are very similar for each size fraction except the mean one; and thus the differences between true and nominal mean diameters in each fraction are about the same for the two lines. Lines (a) and (1) show that this relation is true of any sorting.

TABLE 1.—*Proportional parts of the various size fractions of sedimentary mixtures with a normal size-frequency distribution and various standard deviations. The numbers may be considered as weight percentages although the whole of the distribution may not fall within 14ϕ and thus the total may be less than one hundred percent.*

Dispersion from M_ϕ in phi units	σ_ϕ 0.5	1.0	2.0	4.0
7			0.000492	2.170
6			0.00242	3.245
5		0.000338	0.92	4.575
4		0.02296	2.79	6.050
3		0.5967	6.55	7.515
2	0.135	6.06	12.10	8.790
1	15.735	24.17	17.47	9.640
M_ϕ	68.26	38.30	19.74	9.950
1	15.735	24.17	17.47	9.640
2	0.135	6.06	12.10	8.790
3		0.5967	6.55	7.515
4		0.02296	2.79	6.050
5		0.000338	0.92	4.575
6			0.00242	3.245
7			0.000492	2.170

MATHEMATICAL SOLUTION OF THE PROBLEM

The solution for the area under a portion of a normal probability curve may be obtained from tables in most texts on statistics, as has been noted before. This area is presented as a fractional part of the whole area, and is exactly equal to the weight percentage of a sedimentary size fraction in relation to the whole sample. The area under the curve is usually divided into fractions by measuring distances along the X axis in terms of the standard deviation. Table 1 summarizes the weight percentage of each grain size necessary to synthesize a sand mixture with a probability size-frequency distribution and certain definite standard deviations. The sieve interval is equal to one phi unit, but the table applies to any mean size.

GRAPHICAL SOLUTION

A graphical solution to the present problem is easily constructed by the use of probability paper (Krumbein and Monk, 1942). The size-frequency distribution is a straight line, and the mean and standard deviation are two points

on that line. Figure 1 represents the plots of normal sands with a variety of sortings. Sorting is expressed in terms of phi standard deviation, and grain size in intervals of phi units. Only the upper half of the graph is evident, but the lower half may be read by inverting the page and subtracting the ordinate from 100%. Procedure for determining the weight per cent of any grain size can be shown by using $\sigma_\phi = 1.0$ as an example. The size fraction containing M_ϕ includes all diameter sizes within $\phi/2$ on either side of M_ϕ (if $M_\phi = M_{\phi n}$, and the sieving interval is one phi unit). The weight percentage which corresponds to a nominal mean diameter of $M_\phi + \phi/2$ is about 69 for this sorting.

69 (weight percentage of $M_\phi + \phi/2$)
-50% (weight percentage of M_ϕ)
19%

This percentage must be doubled to take account of the lower half of the curve. The product, 38%, agrees well with the calculated value of 38.3% shown in Table 1. The size fraction which has a $M_{\phi n}$ one phi unit larger than the $M_{\phi n}$ of the mean fraction includes all the grain sizes within the limits of $M_{\phi n} + \phi/2$ to $M_{\phi n} + 3\phi/2$. Applying the method indicated above;

93% (weight percentage of $M_{\phi n} + 3\phi/2$)
-69% (weight percentage of $M_{\phi n} + \phi/2$)
24.5%

Therefore, 24.5 is the approximate weight percentage of a size fraction which has a nominal mean diameter larger by one phi unit than that of the mean size fraction. Since the distribution is symmetrical about the mean, this is also the weight percentage of the size fraction which has a $M_{\phi n}$ smaller by one phi unit than that of the mean size fraction.

An analogous graph can be prepared relating the nominal median diameter in millimeters and the coefficient of sorting to the weight percentage. It is necessary to use logarithmic probability paper instead of the arithmetic type. The straight line corresponding to a desired sand mixture can be drawn by connecting the median to one of the quartiles. The former is given, but the quartile must be calculated from the given coefficient of sorting. This can be done as follows:

$$C_s = \sqrt{\frac{Q_1}{Q_3}}$$

therefore

$$Q_1 = C_s^2 Q_3.$$

The two quartiles are symmetrically disposed around the median so:

$$Md = C_s Q_3$$
$$Q_1 = C_s Md.$$

The weight percentages of each size fraction necessary to synthesize a desired mixture can be determined by use of this type of graph in exactly the same way as was done with Figure 1.

LABORATORY PROCEDURE

The required size fractions may be obtained by sieving a natural sand if only a small quantity of a synthetic sand mixture is desired. Yet if several cubic feet of sand are required, it will usually prove easier to modify a natural sand rather than to sieve all of it. This may be done by sieving part of the sand in order to determine its size-frequency distribution, and also to obtain some quantity of each of the desired grain size fractions. The weight percentage of each size fraction of the natural sand may then be modified by the addition of more or less of the sieved sand until the desired weight percentage of that fraction is obtained. As an example, 100 grams of a sand with a phi standard deviation of 0.5 can be changed to 100 grams of one with the same mean but with a $\sigma_\phi = 1.0$ as shown in Table 2 (data of first two columns from Table 1). Since only 38.30 grams of grain size M_ϕ are required, only 38.30/68.26 ($=0.561$) of the original 100

grams can be used. These 56.1 grams contain the percentage weights for each size fraction which appear in column (3) of Table 2. The weight of each size fraction required to be added to the 56.1 grams of the natural sand in order to synthesize the desired one can be obtained by subtracting the figures in column (3) from those in column (2). The results appear in column (4).

This method of modification may be particularly useful if it is desired to produce a large number of sands of various sortings; each one can be modified from the one with the next better sorting. Some limitations on the method have been mentioned under the discussion of the true and nominal mean diameters. Thus the example of modification selected would be undesirable because the sieve interval of one phi unit is too large to make the true and nominal mean diameters reasonably equal for all size fractions. The limits of error in any proposed experiments would govern the acceptability of any modification.

The actual physical mixing of the sand must be done so as to insure homogeneity. This may be accomplished by the methods commonly used to obtain a composite sample.

USES FOR SYNTHETIC SAND MIXTURES

Synthetic sand mixtures should find their greatest use in the experimental laboratory. They make it possible to vary the mean and the standard deviation in a systematic manner, and thus to evaluate the effect of these variables upon the process under consideration. Krumbein and Monk (1942) used such mixtures in measuring the influence of sedimentary parameters upon permeability. The author used them in an attempt to determine the relation between sorting and competent velocity.

However, other uses appear possible. Emery (1948) has shown that rapid size analyses of a great many specimens may be achieved by visual comparison with natural sediments which have a known size-frequency distribution. Synthetic sands should provide an easy means of obtaining a known suite in which each specimen varies from the next in accordance with a predetermined limit of accuracy rather than the chance variation in a natural suite.

TABLE 2.—*The numbers are weights in grams. Columns (1) and (2) represent normal size-frequency distributions for the standard deviations indicated. See text for significance and use of table.*

Dispersion from M_ϕ in phi units		(1) $\sigma_\phi = 0.5$	(2) $\sigma_\phi = 1.0$	(3) $0.561 \times (1)$	(4) $(2) - (3)$
	4		0.02		0.02
	3		0.60		0.60
	2	0.135	6.06	0.076	5.98
	1	15.735	24.17	8.83	15.34
	M_ϕ	68.26	38.30	38.30	0.0
	1	15.735	24.17	8.83	15.34
	2	0.135	6.06	0.076	5.98
	3		0.60		0.60
	4		0.02		0.02

BIBLIOGRAPHY

DOEGLAS, D. J., *1946*. Interpretation of the results of mechanical analyses: *Jour. Sed. Pet.*, vol. 16, no. 1, pp. 19–40.

EMERY, K. O., and GOULD, H., *1948*. A code for expressing grain size distribution: *Jour. Sed. Pet.*, vol. 18, no. 1, pp. 14–23.

KRUMBEIN, W. C., *1936*. Application of logarithmic moments to size frequency distributions of sediments: *Jour. Sed. Pet.*, vol. 6, no. 1, pp. 35–47.

———, *1938*. Size frequency distribution of sediments and the normal phi curve: *Jour. Sed. Pet.*, vol. 8, no. 3, pp. 84–91.

———, *1939*. Graphic presentation and statistical analyses of sedimentary data: Recent marine sediments, Trask, ed., pp. 558–591, *Am. Assoc. Pet. Geol.*

———, and MONK, G. D., *1942*. Permeability as a function of the size parameters of unconsolidated sand: A.I.M.E., *Petroleum Technology*, vol. 5, no. 4, 11 pp.

OTTO, G. H., *1939*. A modified logarithmic probability graph for the interpretation of mechanical analyses of sediments: *Jour. Sed. Pet.*, vol. 9, no. 2, pp. 62–76.

Contribution No. 471

Made in United States of America

Reprinted from JOURNAL OF THE WASHINGTON ACADEMY OF SCIENCES
Volume 39, No. 11, November 15, 1949

ZOOLOGY.—*Echinoderms from the mid-Atlantic dredged by the* Atlantis *in the summer of 1948.*[1] AUSTIN H. CLARK, U. S. National Museum.

Through Dr. Louis W. Hutchins the Woods Hole Oceanographic Institution has submitted to me for study an unusually interesting collection of sea-stars, brittle-stars, sea-urchins, and sea-lilies from the mid-Atlantic, largely from the general vicinity of the Azores. This collection was made by the *Atlantis* of the Woods Hole Oceanographic Institution on cruise no. 152, sponsored jointly by the National Geographic Society, Columbia University, and the Woods Hole Oceanographic Institution. It is especially interesting in including a number of species that have not been found since the days of the *Challenger*, *Travailleur*, *Talisman*, *Hirondelle*, and *Princesse-Alice*. For the pleasure of studying this collection I am deeply indebted to the Woods Hole Oceanographic Institution and to Dr. Hutchins.

[1] Contribution from the Woods Hole Oceanographic Institution No. 471. Published by permission of the Secretary of the Smithsonian Institution. Received April 25, 1949.

ASTEROIDEA

ASTROPECTINIDAE

Leptychaster arcticus (M. Sars)

Astropecten arcticus M. Sars, Reise i Lofoten og Finmarken, Nyt Mag. for Naturvid. **6**: 161. 1851.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 53′ W.); 85 fathoms; July 31, 1948. Thirteen specimens.

Note.—In all the specimens R = about 30 mm.

Plutonaster notatus Sladen

Plutonaster notatus Sladen, *Challenger* Reports, Zoology, **30** (pt. 51): 97, pl. 14, figs. 6, 7, pl. 15, figs. 5, 6. 1889.

Locality.—*Atlantis* cruise 152, station 28; southwest of the Azores (lat. 34° 50′ N., long. 39° 20′ W.); 1,770 fathoms; August 30, 1948. Three specimens.

Notes.—One of the specimens measures R = 25 mm., r = 8 mm.; in the other two R = 22 mm., r = 8 mm. In one specimen many and in the others a few of the papillae on the abactinal surface have 2 to 4 (usually 3) of the central spines enlarged and swollen, forming a pedicellaria. Two of the specimens have a few similar pedicellariae on the actinal surface.

Dytaster biserialis Sladen

Dytaster biserialis Sladen, *Challenger* Reports, Zoology, **30** (pt. 51): 77, pl. 10, figs. 3, 4, pl. 13, figs. 3, 4. 1889.

Locality.—*Atlantis* cruise 152, station 8; west of Newfoundland and south of Greenland (lat. 47° 10′ N., long. 36° 00′ W.); 2,300 fathoms; August 2, 1948. One specimen.

Notes.—In this specimen R = 43 mm., r = 9 mm.; there are 28 marginals.

Dytaster mollis (E. Perrier)

Crenaster mollis E. Perrier, Expéditions scientifiques du *Travailleur* et du *Talisman* pendant les années 1880, 1881, 1882, 1883, Échinodermes: 310, pl. 18, figs. 3, a, b. 1894.

Locality.—*Atlantis* cruise 152, station 20; west of San Miguel, Azores (lat. 37° 50′ 30″ N., long. 26° 00′ W.); 1,400 fathoms; August 18, 1948. One specimen.

Notes.—There seems to be no doubt that this specimen represents Perrier's *Crenaster mollis*, which was described from a single individual dredged southwest of Terceira, Azores (lat. 38° 38′ N., long. 27° 26′ W.), in 2,995 meters. It does not quite agree in some respects with Perrier's description, which differs slightly from his figures, so that it appears desirable to describe it in detail.

Description.—R = 40 mm., r = 9 mm. The form is stellate with the angles of the star produced into long narrow arms and the interbrachial arcs broadly and regularly rounded.

The plates of the abactinal surface are small, 4 or 5 to a millimeter in the central portion of the disk and along the middle of the rays, gradually becoming larger toward the borders of the interradial areas and rather abruptly larger in the two rows adjacent to the superomarginals, both on the disk and on the arms. The plates are very delicate, thin and glassy, subcircular or polygonal, and where there are interstices between them these are bridged by thin filmy scale-like plates, the whole forming a continuous mosaic. The surface of each plate, except for a narrow glassy rim, is abruptly raised into a stout opaque cylindrical tubercle with a broadly rounded summit, these tubercles being mostly higher than thick; the large tubercles along the interradial margins of the disk are more or less capitate. Each tubercle bears on its summit a group of commonly 6–9 spines arranged in a circle, with or without a central spine. These spines are usually somewhat longer than the tubercle is high, and are slightly flaring and thorny in the distal half. The madreporite is large, situated near the interradial border and almost in contact with the superomarginals. It is surrounded by a ring of about 15 somewhat enlarged spine-bearing tubercles, and carries 4 much enlarged spine-bearing tubercles on its surface.

As viewed from the side the marginals of the two series are equal in size and similar, and the superomarginals lie directly over the inferomarginals so that the line separating them, and the vertical lines separating the pairs, are straight and at right angles to each other. The marginals decrease slowly and regularly in size from the interbrachial arcs outward to the tips of the rays. In the interbrachial arcs the marginals are square, but they soon become about half again as long as broad, in the outer third of the rays slowly decreasing in length and becoming square at some distance from the tips. The inferomarginals encroach more on the actinal than the superomarginals do on the abactinal surface. There are about 30 marginals from the middle of the interbrachial arcs to the tips of the rays.

Viewed on the abactinal surface the two superomarginals in the middle of the interbrachial arcs are slightly higher (radially) than broad. The one on each side of this pair is about as long as

broad, and those following soon become about half again as long as broad, in the distal third of the ray slowly decreasing in length and becoming about as long as broad near the tip, with the last few slightly broader than long. The terminal plate is rather large, broadly truncate distally with converging sides and the inner end excavated in approximately a right angle. The superomarginals bear numerous scattered thorny spinules which are separated by about their own length. The two in the middle of each interbrachial arc bear a short slender conical spine, and the one on each side of these bears two smaller spines. None of the others bear spines.

The inferomarginals are covered with scattered spinules similar to those on the superomarginals. The two in the middle of each interbrachial arc bear two median conical spines. The next 15 or 16 on each side each bear a single slender short spine decreasing in size distally, at first central and surrounded by enlarged spinules, soon losing the accompanying enlarged spinules and gradually moving to the distal end of the plates.

On the actinal surface the interactinal areas are occupied by a number of plates which are much larger than the plates of the abactinal surface and are only slightly convex. A somewhat irregular median row runs from the suture between the mouth plates to the suture between the two central inferomarginals; this includes 3 or 4 plates; except for a single plate adjoining the mouth plates, it is absent in one interactinal area. Perrier does not mention this unpaired column in his description, but it appears to be indicated in his figure of the actinal surface (1a). On each side of this there is a column of 3 plates, with a small one next the inferomarginal. Perrier says that these columns have 5 or 6 plates, but his figure seems to show 3 or 4. These columns are followed by a column of 3 plates and a very small one, then two plates and a very small one, then about 4 single plates between the adambulacrals and inferomarginals. The two median inferomarginals each have 4 columns of plates abutting against their inner ends, and those adjacent have 2 or 3. There are 3 columns of plates arising from the mouth plates, and 4 from the first 3 adambulacrals; usually 2 plates adjoin the fourth and fifth adambulacrals, followed by long very narrow plates between the following adambulacrals and inferomarginals. These plates bear usually 12–15 well-spaced spinelets scattered uniformly over the surface which resemble those of the inferomarginals and are much larger than those of the abactinal plates.

The number of adambulacrals is greater than that of the inferomarginals so that the two series do not exactly correspond until about the tenth inferomarginal, which corresponds to the thirteenth adambulacral; from this point on the two series correspond. The inner border of the adambulacrals is regularly curved and bears a comb of 9 slender spines of which the two outermost are the shortest. On the outer edge of the plate there is a straight row of 6 or 7 subequal shorter and rougher spines. In the distal third of the arms the adambulacrals develop a single long spine on the actinal surface.

The mouth plates were well described by Perrier. There are no pedicellariae.

Goniasteridae

Hippasterinae

Hippasteria phrygiana (Parelius)

Asterias phrygiana Parelius, Kgl. norwegischen Ges. Wiss. (zu Drontheim) Schriften, aus dem dänischen Übersetzt, Teil 4: 349, 350, pl. 15, figs. 1, 2. 1768.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. One specimen.

Notes.—This specimen is large, with R = 175 mm., r = 75 mm. The disk is subcircular and tumid, abruptly separated from the rays, which are 30 mm. wide at the base and are separated from each other by a distance of 60 mm. The rays are high and evenly rounded abactinally.

Especially remarkable is the great size of the pedicellariae. Those on the abactinal surface are 3 mm. long. On the actinal intermediate plates the numerous pedicellariae are about 5 mm. long. Each of the plates of the series between the inferomarginals and the adambulacrals bears an enormous pedicellaria; on the disk these are set at an angle of about 60° to the ambulacral groove, but on the rays they are more or less at right angles to it. On the disk these pedicellariae are from 6 to 10 (mostly about 8) mm. long; on the rays they slowly decrease to 3 mm. at the end of the series, about 20 mm. from the tips.

Asteropidae

Poraniomorpha borealis (Verrill)

Asterina borealis Verrill, Amer. Journ. Sci. **16:** 213. 1878.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. One specimen.

Note.—The single specimen is large, with R = 57 mm., r = 37 mm.

ECHINASTERIDAE

Henricia sanguinolenta (O. F. Müller)

Asterias sanguinolenta O. F. Müller, Zoologiae Danicae Prodromus: 234. Havniae, 1776.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. Thirty-one specimens.

Note.—In these specimens R = 11 to 37 mm.

Henricia lisa, n. sp.

Description.—The single specimen is in poor condition. It was completely encased in mud and ooze the removal of which resulted in the loss of most of the spines.

R = 26 mm. r = 7 mm. The form is stellate with the points of the star much produced. The arms taper rapidly to about 15 mm. from the center of the disk, thence slowly to the rounded tip. The interradial arcs form an obtuse angle with straight sides. The disk and the stout basal portion of the arms were apparently inflated in life.

The abactinal skeleton is very dense, composed of a great number of small and mostly slightly elongated plates among which are interspersed rounded or polygonal plates, especially about the papular pores, with occasional small independent subcircular plates in the interstices. Numerous single papulae occur between the plates, except in a broad line from the middle of the interbrachial arcs about half way to the center of the disk where the plates are larger and shorter than elsewhere with the inner ends elevated and imbricating, and are closely appressed against each other with no interspaces. Presumably in life this solid line of plates was depressed, forming a sulcus. All the plates are strongly and smoothly convex.

The abactinal skeleton in general resembles that of certain forms of *Henricia leviuscula*, but the plates are much smaller, lower, and more densely packed, all the papulae being single.

Each plate appears to bear a regular or irregular row of usually 3 or 4, sometimes 2 or even only 1, short and fine spines; on the plates in the interradial lines there are usually 2, sometimes 1 or 3, spines on the highest (inner) portion.

The madreporite, situated about half way between the center and margin of the disk, is large and prominent, about 2 mm. in diameter, and, in the dry specimen, is elevated above the surface of the disk. It is coral-like, but bears a number of spines scattered over its surface.

The plates of the abactinal surface are continued around the margin of the disk onto the actinal surface where they become somewhat higher with a more or less developed median crest. Except in a broad central band, a continuation of the interradial band of the abactinal surface, which reaches nearly to the mouth plates, they become aligned with their long axes at right angles to the margin of the disk and arranged in somewhat irregular transverse and longitudinal rows. The inferomarginals, scarcely distinguishable from the other plates, are separated from the adambulacrals by a single row of actinal intermediate plates which extends at the twentieth or twenty-fourth adambulacral. Near the mouth plates the plates of the actinal intermediate series are as large as, or larger than, the inferomarginals and bear a comb of 2–4 spinelets, but they soon decrease in width and become subcircular.

The two series of inferomarginals in each actinal interradial area almost meet just beyond the mouth plates, being separated by the narrow inner end of the irregular band of plates in the middle of the areas. The superomarginals are indistinguishable in these areas. There is a more or less deficient row of papulae between the inferomarginals and the actinal intermediate plates. The plates of the interradial areas bear a row of 4–6 spinelets resembling those on the abactinal surface but longer.

The adambulacral plates are short and broad, the largest plates on the rays. They bear a regular or somewhat irregular row of 6–8 spines of which the innermost (sometimes the two innermost) is abruptly larger and stouter than the others, which are short and decrease in length outwardly. At the inner angle of the plate, deep within the furrow, there is a stout conical spine, shorter than the large spine at the end of the series on the actinal surface.

The mouth plates are about three times as long as broad. The two of each pair curve about a broad central cavity, being separated at their

outer ends but broadly in contact at their tips. Each mouth plate bears a series of about 7 stout spines along the outer edge, and a similar series along the inner edge. Each pair of mouth plates has at the tip a single unpaired spine.

Type.—U.S.N.M. no. E. 7774, from *Atlantis* cruise 152, station 8; southeast of Newfoundland and west of the Azores (lat. 47° 10′ N., long. 36° 00′ W.); 2,300 fathoms; August 2, 1948.

Notes.—It is with much diffidence that I propose a new specific name in this perplexing genus, but the present specimen is so different from any previously recorded that it seems reasonable to assume that it represents a new specific type. Of all the named species and forms it comes nearest to *Henricia sanguinolenta eschrichtii* forma *tumida* Verrill as represented by some specimens at hand from the Bering Sea area, with unusually dense abactinal skeletons. But the rays are tumid only in the proximal half, the skeleton is more compact and composed of smaller plates which are evenly rounded dorsally without ridges or bosses, the marginal plates are not clearly defined, the spinelets on all the plates are longer and more slender, and the papulae are invariably single.

PTERASTERIDAE

Pteraster militaris (O. F. Müller)

Asterias militaris O. F. Müller, Zoologiae Danicae Prodromus: 234. Havniae, 1776.

Locality.—*Atlantis* cruise 152, station 6, east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. One specimen.

Notes.—The single specimen is four-rayed; R = 16 mm., r = 7 mm.

BRISINGIDAE

Freyella abyssicola E. Perrier

Freyella spinosa var. *abyssicola* E. Perrier, Expéditions scientifiques du *Travailleur* et du *Talisman* pendant les années 1880, 1881, 1882, 1883, Échinodermes: 88. 1894. One specimen.

Locality.—*Atlantis* cruise 152, station 8; east of Newfoundland and south of Greenland (lat. 47° 10′ N., long. 36° 00′ W.); 2,300 fathoms; August 2, 1948.

Notes.—The single specimen has the disk 11 mm. in diameter and the 11 rays 85 mm. long. Four of the rays, opposite the madreporite, are slightly smaller than the others.

This specimen agrees closely with Perrier's type from northeast of the Azores (lat. 42° 19′ N., long. 23° 36′ W.), in 4,060 meters, which also had 11 rays.

ASTERIIDAE

PEDICELLASTERINAE

Hydrasterias ophidion Sladen

Asterias (*Hydrasterias*) *ophidion* Sladen, *Challenger* Reports, Zoology, **30** (pt. 51): 581, pl. 99, figs. 3, 4, pl. 103, figs. 3, 4. 1889.

Locality.—*Atlantis* cruise 152, station 20; north of the Azores (lat. 37° 50′ 30″ N., long. 26° 00′ W.); 1,400 fathoms; August 18, 1948. 10+ specimens.

Notes.—All the specimens have 6 rays; R = about 35 mm.

ASTERIINAE

Asterias vulgaris Verrill

Asterias (*Asteracanthion*) *vulgaris* (Stimpson, MS.) Verrill, Proc. Boston Soc. Nat. Hist. **10:** 347. 1866.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. One specimen.

Note.—The single specimen is small, with R = 11 mm.

OPHIUROIDEA

OPHIACANTHIDAE

Ophiacantha abyssicola G. O. Sars

Ophiacantha abyssicola G. O. Sars, Nye Echinod. fra den norske Kyst., Vid. Selsk. Forh. Christiania: 8. 1871.

Locality.—*Atlantis* cruise 152, station 26; southwest of the Azores (lat. 34° 12′ 30″ N., long. 30° 12′ 30″ W.); 570 fathoms; August 26, 1948. One small specimen.

OPHIACTIDAE

Ophiactis abyssicola (M. Sars)

Amphiura abyssicola M. Sars, Norges Echin.: p. 18, pl. 2, figs. 7–12. 1861.

Locality.—*Atlantis* cruise 152, station 11; north of the Azores (lat. 42° 53′ 30″ N., long. 29 05′ W.); 720 fathoms; August 10, 1948. Two specimens.

Ophiopholis aculeata (Linné)

Asterias aculeata Linné, Syst. Nat., ed. 12, **1** (pt. 2): 1101, No. 12. 1767.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. Thirty-eight specimens.

Note.—All the specimens are small, the largest having the disk 9 mm. in diameter.

OPHIOLEPIDIDAE

Amphiophiura convexa (Lyman)

Ophioglypha convexa Lyman, Bull. Mus. Comp. Zool. **5:** 84, pl. 3, figs. 83, 84. 1878.

Localities.—*Atlantis* cruise 152, station 8; east of Newfoundland and south of Greenland (lat. 47° 10′ N., long. 36° 00′ W.); 2,300 fathoms; August 2, 1948. Eleven specimens.

Station 30; between North Carolina and the Azores (lat. 34° 53′ N., long. 46° 24′ W.); 2,530 fathoms; September 3, 1948. One specimen.

Notes.—The largest specimen from station 8 has the disk 15 mm. in diameter and the arms 30 mm. long. The single specimen from station 30 has the disk 12 mm. in diameter and the arms 24 mm. long.

Ophiura sarsii Lütken

Ophiura sarsii Lütken, Vidensk. Meddel., 1854: 101. 1855.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. Six specimens.

Note.—The largest specimen has the disk 20 mm. in diameter.

Ophiura irrorata (Lyman)

Ophioglypha irrorata Lyman, Bull. Mus. Comp. Zool. **5:** 73, pl. 4, figs. 106–108. 1878.

Locality.—*Atlantis* cruise 152, station 8; east of Newfoundland and south of Greenland (lat. 47° 10′ N., long. 36° 00′ W.); 2,300 fathoms; August 2, 1948. Three specimens.

Note.—The largest specimen has the disk 23 mm. in diameter and the arms 125 mm. long.

Ophiura ljungmani (Lyman)

Ophioglypha ljungmani Lyman, Bull. Mus. Comp. Zool. **5:** 71, pl. 3, fig. 77. 1878.

Locality.—*Atlantis* cruise 152, station 11; north of the Azores (lat. 42° 53′ 30″ N., long. 29° 05′ W.); 720 fathoms; August 10, 1948. Five specimens.

Note.—The largest specimen has the disk 6 mm. in diameter and the arms 16 mm. long.

Ophiocten sericeum (Forbes)

Ophiura sericea Forbes, Journ. Sutherland's Voy. **2:** App.: 215. 1852.

Locality.—*Atlantis* cruise 152, station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948. 203 specimens.

Note.—All the specimens are small, the largest with the disk about 5 mm. in diameter.

ECHINOIDEA

STRONGYLOCENTROTIDAE

Strongylocentrotus dröbachiensis (O. F. Müller)

Echinus dröbachiensis O. F. Müller, Zoologiae Danicae Prodromus: 235. Havniae, 1776.

Locality.—*Atlantis* cruise 152, station BT 65; 200 meters; July 21, 1948. One specimen.

Note.—The specimen is 36 mm. in diameter.

SCUTELLIDAE

Echinarachnius parma (Lamarck)

Scutella parma Lamarck, Hist. nat. des animaux sans vertèbres **3:** 11. 1816.

Locality.—*Atlantis* cruise 152, station 1; south of Nantucket, Massachusetts (lat. 40° 50′ N., long. 70° 10′ W.); 19–20 fathoms; July 16, 1948. One specimen.

Note.—The single specimen is 38 mm. in diameter.

PALAEOPNEUSTIDAE

Homolampas fragilis (A. Agassiz)

Lissonotus fragilis A. Agassiz, Bull. Mus. Comp. Zool. **1:** 273. 1869.

Locality.—*Atlantis* cruise 152, station 20; north of the Azores (lat. 37° 50′ 30″ N., long. 26° 00′ W.); 1,400 fathoms; August 18, 1948. Fragments of 2 medium-sized specimens, one living and one dead.

CRINOIDEA

BOURGUETICRINIDAE

Democrinus parfaiti E. Perrier

Democrinus parfaiti E. Perrier, Comptes Rendus **96** (7): 450. 1883.

Locality.—*Atlantis* cruise 152, station 11; north of the Azores (lat. 42° 53′ 30″ N., long. 29° 05′

W.); 720 fathoms; August 10, 1948. One specimen, without arms.

Notes.—This specimen consists of a root, stem, basals, and radials. The stem is about 105 mm. long with 55 columnals, and the basals are 3 mm. long.

BATHYCRINIDAE

Bathycrinus aldrichianus Wyville Thomson

Bathycrinus aldrichianus Wyville Thomson, Journ. Linn. Soc. (Zool.) **13:** pp. 47–51, fig. 1. 1876.

Bathycrinus serratus A. H. Clark, Proc. U. S. Nat. Mus. **34:** 205, fig. 1; 306. 1908.

Locality.—Between North Carolina and the Azores (lat. 34° 53′ N., long. 46° 24′ W.); 2,530 fathoms; September 3, 1948. One stem without the proximal portion, and fragments of another.

Notes.—The larger fragment is about 122 mm. long with 61 columnals, tapering to a diameter of 0.4 mm. at the broken proximal end. The longest columnals, near the broken end, are 1.5 mm. long and about four times as long as broad, and are cylindrical. The other smaller fragments are from a considerably stouter stem.

Prof. Torsten Gislén has suggested to me that my *Bathycrinus serratus* described in 1908 from *Albatross* station 2226, off Virginia in 2,045 fathoms, and recorded from *Albatross* station 2713, off Maryland in 1,859 fathoms, is in reality a synonym of Prof. Wyville Thomson's *B. aldrichianus*. With this suggestion I am quite in agreement.

LIST OF THE STATIONS, WITH THE SPECIES FOUND AT EACH

Station 1; south of Nantucket (lat. 40° 50′ N., long. 70° 10′ W.); 19–20 fathoms; July 16, 1948:

Echinarachnius parma

Station 6; east of southern Newfoundland and south of Cape Farewell, Greenland (lat. 47° 08′ N., long. 44° 52′ W.); 85 fathoms; July 31, 1948:

Leptychaster arcticus
Hippasteria phrygiana
Poraniomorpha borealis
Henricia sanguinolenta
Pteraster militaris
Asterias vulgaris
Ophiopholis aculeata
Ophiura sarsii
Ophiocten sericeum

Station 8; west of Newfoundland and south of Greenland (lat. 47° 10′ N., long. 36° 00′W.); 2,300 fathoms; August 2, 1948:

Dytaster biserialis
Henricia lisa
Freyella abyssicola
Amphiophiura convexa
Ophiura irrorata

Station 11; north of the Azores (lat. 42° 53′ 30″ N., long. 29° 05′ W.); 720 fathoms; August 10, 1948.

Ophiactis abyssicola
Ophiura ljungmani
Democrinus parfaiti

Station 20; west of San Miguel, Azores (lat. 37° 50′ 30″ N., long. 26° 00′ W.); 1,400 fathoms; August 18, 1948:

Dytaster mollis
Hydrasterias ophidion
Homolampas fragilis

Station 26; southwest of the Azores (lat. 34° 12′ 30″ N., long. 30° 12′ 30″ W.); 570 fathoms; August 26, 1948:

Ophiacantha abyssicola

Station 28; southwest of the Azores (lat. 34° 50′ N., long. 39° 20′ W.); 1,770 fathoms; August 30, 1948:

Plutonaster notatus

Station 30; between North Carolina and the Azores (lat. 34° 53′ N., long. 46° 24′ W.); 2,530 fathoms; September 3, 1948:

Amphiophiura convexa
Bathycrinus aldrichianus

Station BT 65; 200 meters:

Strongylocentrotus dröbachiensis

Contribution No. 472

THEORETICAL ANALYSIS OF SEASONAL CHANGES IN THE PHYTOPLANKTON OF HUSAN HARBOR, KOREA

By

GORDON A. RILEY AND RUTH VON ARX

Woods Hole Oceanographic Institution [1]

INTRODUCTION

It has been shown (Riley, 1946, 1947) that seasonal changes in total phytoplankton populations can be depicted with a reasonable degree of accuracy by a simple theoretical construction in which the rate of change of the population is described in terms of physiological processes that increase or decrease its organic content (photosynthesis, respiration, grazing), and in which the rates of the individual processes are quantitatively predictable by reference to a few environmental factors. In the papers cited, an examination was made of the seasonal cycles of phytoplankton in the Georges Bank area of the Gulf of Maine and in coastal waters south of New England. The cycles were markedly different, but the same equation was applicable in each case, suggesting that variations in the cycles were attributable to simple environmental differences in the two areas.

These papers fall far short of a definitive treatment of the problems of plankton variation. The general principles appear to be sound, but the details of the application are greatly over-simplified. Improvements in method will require more complete laboratory and field data, but the success of these future investigations will be more secure if the problems are further clarified by continuing the examination of existing data. One phase of the problem that has been studied recently is the regional distribution of plankton (Riley, Stommel and Bumpus, 1949). Another phase, to be investigated here, is the ecological basis for differences that occur in plankton cycles from one year to the next. The chief requirement for such a study is a very complete set of data on both the plankton and its environment. A survey of Husan Harbor, Korea, was found to be particularly suitable for the purpose.

MATERIAL

A survey of the neritic plankton of Japanese waters was summarized by Kokubo (1940) and published more extensively (in Japanese)

[1] Contribution No. 472 from the Woods Hole Oceanographic Institution.

Reprint from SEARS FOUND. JOURN. MAR. RES.

in a series of papers in the *Plankton Journal.* The survey was sponsored by the National Research Council of Japan on the recommendation of a conference of some of the leading marine biologists of that country. H. Marukawa, F. Fugita, S. Suzuki, and other investigators cooperated with Kokubo in a program resulting in the collection and examination of some 450 samples at 16 stations lying between 25° and 47° North and covering the period from 1931 to 1933. Collections consisted of 10 l. of surface water taken approximately one mile off shore, usually with accompanying data on temperature, specific gravity, transparency, and water color. The collections were allowed to stand 24 hours after preservation with formalin, and the volume of sediment and numbers of organisms were then determined.

Fig. 1 shows Kokubo's observations in Husan Harbor. They were ably supplemented by a survey conducted by the Imperial Fisheries Experiment Station of Korea during 1932 and 1933, the results of which were published in tabular form in the annual reports of that

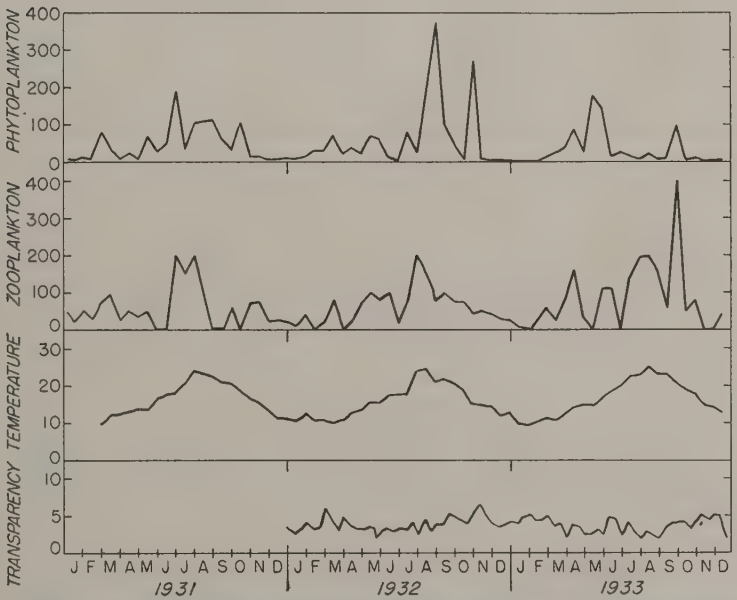

Figure 1. Seasonal cycles in Husan Harbor, Korea. Phytoplankton, thousands of cells per liter; zooplankton, number of organisms per liter; temperature, degrees Centigrade; transparency, Secchi disc reading in meters (Kokubo, 1940).

institution. Their data on nutrient salts and hours of sunshine per month, reproduced in Fig. 2, will form an important part of the analysis.

QUALITATIVE DISCUSSION

The phytoplankton data in Fig. 1 show rather large differences from one year to the next in the relative magnitude of spring and summer-autumn flowerings, the size and duration of the flowerings, and the degree of depletion following them. Differences are also apparent in zooplankton and in physical and chemical factors of the environment. Inspection of the data reveals some slight evidence of causality in these variations. The zooplankton curve suggests an inverse relation between the size and duration of the summer maximum in zooplankton and the size of the summer-autumn phyto-

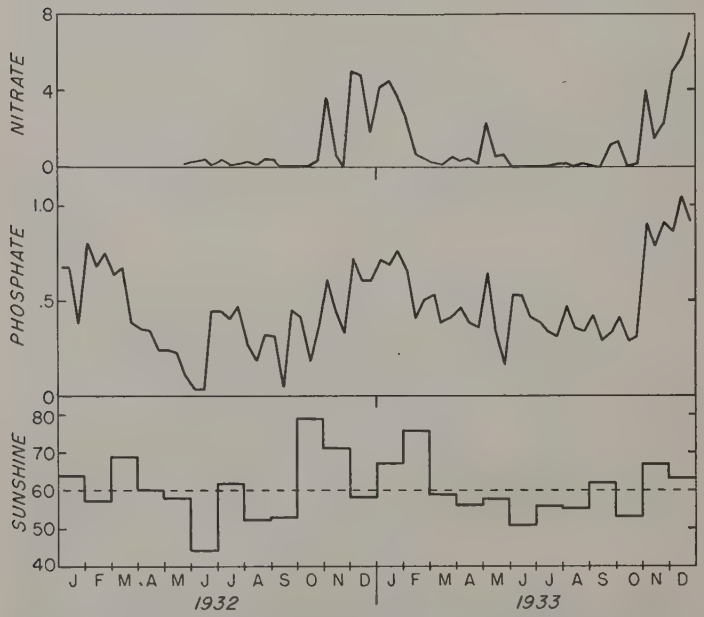

Figure 2. Seasonal cycles in Husan Harbor, Korea. Milligram-atoms of nitrate-N and phosphate-P per m^3; number of hours of sunshine per month (Annual Report of the Imperial Fisheries Experiment Station of Korea, 1932, 1933).

plankton flowering, and therefore zooplankton grazing may be important in controlling the size of the summer phytoplankton population. Comparison with Fig. 2 shows that near-depletion of phosphate and absence of nitrate were accompanied by a decline in the phytoplankton population; in 1933, when there was no phytoplankton flowering until midautumn, the nitrate concentration was considerably lower than in 1932, when there was a large summer flowering. The beginning of each summer and autumn flowering—July and October 1932 and September 1933—occurred during months when the amount of sunshine was above average.

These considerations suggest that phytoplankton variations from one year to the next might be explained reasonably in terms of environmental influences. However, the relationship seems likely to be a complicated one, involving a number of factors, so that conclusive results are not to be obtained by simple inspection.

QUANTITATIVE ANALYSIS

It will be assumed initially that the processes of increase and decrease of the phytoplankton population are accurately expressed by a simple equation

$$\frac{dP}{dt} = P(P_h - R - G) \ , \tag{1}$$

in which $\frac{dP}{dt}$, the change in the population during a unit of time, is equal to the initial population P times the sum of the coefficients of the physiological processes involved, namely photosynthesis P_h, phytoplankton respiration R, and grazing G. Furthermore, since growth of phytoplankton takes the form of a geometrical progression, an initial population P_o will change during the time interval O to t according to the formula

$$P_t = P_o e^{(P_h - R - G)t} \ , \tag{2}$$

provided the coefficients remain constant during this time, and the relation between the initial population P_o and the final one P_t is expressed by

$$ln \frac{P_t}{P_o} = P_h - R - G \ . \tag{3}$$

These equations assume that the plankton populations either remain stationary or are horizontally uniform. If lateral water movements change the populations, additional expressions must be included to account for such changes.

The equations acquire ecological significance if the physiological coefficients can be rated quantitatively according to environmental influences. It then becomes possible to set up equations predicting the population change during some small interval of time in which the environmental factors can be presumed to remain relatively constant. Comparison of the observed with the predicted population changes provides a quantitative estimate of the accuracy of the method. If it proves to be adequate, the analysis immediately reveals reasons for observed differences in population growth.

In other regions where these methods have been applied, physiological experiments provided much of the necessary information for setting up the equations. These are lacking in the present case. It will be necessary to assume that the results obtained in other areas are sufficiently general in their applicability to warrant using them as a first approximation, after which statistical procedures can be used for any modifications that seem necessary because of local peculiarities or differences in observational methods.

The environmental factors will now be examined, and an attempt will be made to combine them in such a way as to express the physiological effects as accurately as possible. Beginning with photosynthesis, it is first necessary to determine the amount of light available for plankton growth and its annual fluctuations. The sunshine data in Fig. 2 supply only a partial answer to this problem because the amount of solar energy in the sunshine varies with the season according to the altitude of the sun and also because there is a considerable amount of energy derived from sky radiation on cloudy days. Thus Fig. 3, which reproduces data on total radiation from Kimball (1928), shows a large seasonal variation that is not apparent in Fig. 2.

The solid line in Fig. 3 is a generalized curve for latitude 36° N., approximately the latitude of Husan. The broken curve is for 36° N., 131°–140° E., and therefore is more precisely applicable to Husan, taking into account local variations in humidity and cloud cover. Some of the peculiarities of this curve are reflected in Fig. 2 in the tendency toward greater than average sunshine in midwinter and a low value in June. Thus the variations in Fig. 2 are in part normal for the area and in part random variation around the norm. Furthermore, a statistical comparison of the differences in the two figures can be used to estimate roughly the variations in absolute radiation during the two-year period. Thus a least squares fit was obtained between the deviation of hours of sunshine from the average (Fig. 2) and the difference between the two curves in Fig. 3. The resulting equation stated hours of sunshine for any one month in terms of

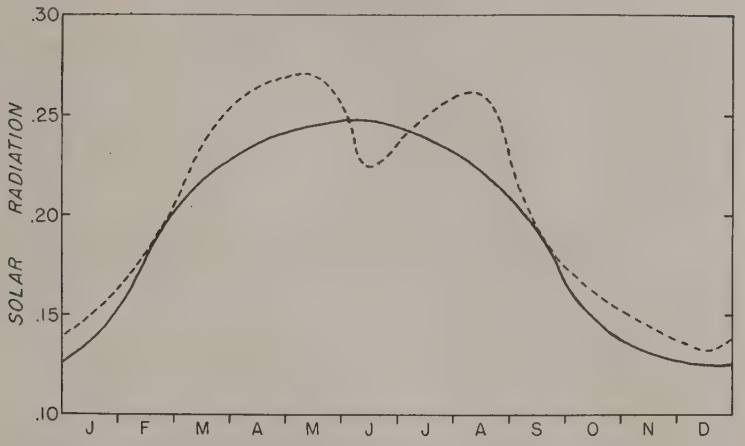

Figure 3. Incident solar radiation in g. cal. per cm² per minute. Solid line, generalized curve for Lat. 36° N.; broken line, average for 36° N., 131°–140° E.

calorific deviation from the average (solid line in Fig. 3). The estimated radiation so obtained is shown as the upper curve in Fig. 4.

Of course this is radiation at the surface of the sea. The amount obtained by the plankton at any depth depends on both the incident radiation and the transparency of the water. It is asumed at this point that the shallow water (average depth 7.7 m.) where collections were obtained was mixed thoroughly enough so that there would be no serious error in stating the effective radiation as the average light intensity in the whole water column. This is obtained by integrating the radiation from surface to bottom and dividing by the depth of water, namely

$$\bar{I} = \frac{I_o}{7.7K}\,(1 - e^{-7.7K}),$$

where I is average radiation in the whole water column in g. cal. per cm² per minute, I_o is incident solar radiation (Fig. 4), and K is the absorption coefficient, estimated as 1.7 divided by the Secchi disc reading in meters (Fig. 1). The average radiation so obtained is the solid line in the middle graph in Fig. 4.

The effectiveness with which phytoplankton uses the available radiation in photosynthesis depends in part on the availability of nutrient salts. In experimental studies of the photosynthesis and growth of pure diatom cultures and of natural populations of the

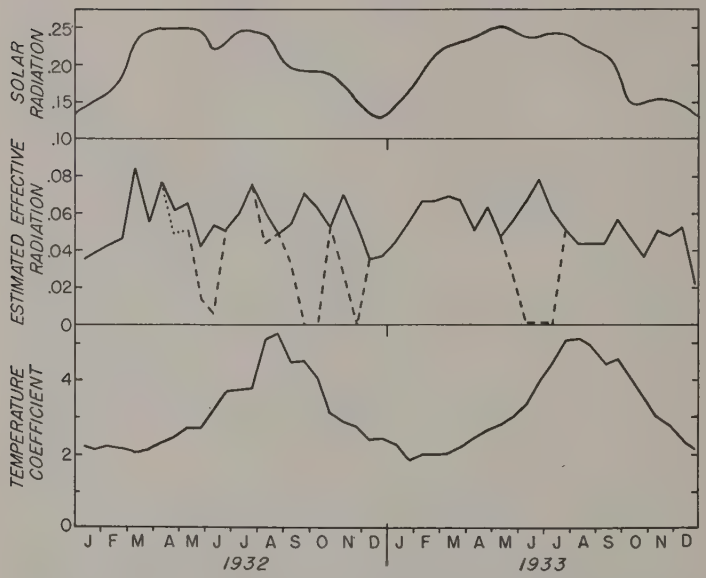

Figure 4. Upper curve, estimated incident solar radiation in g. cal. per cm² per minute; for details of calculation see text. Middle graph, solid line shows estimated average radiation in a column of water 7.7 m. deep in Husan Harbor, based on incident radiation and transparency data. Broken line shows reduction in the potential photosynthetic effect of radiation that is believed to result from depletion of nitrate or phosphate. Dotted line is a similar type of reduction estimated from phosphate alone, during a period when no nitrate data were available. Lower graph shows the relative variation in physiological rates resulting from seasonal temperature changes, on the assumption that these rates are doubled by a ten-degree increase in temperature.

western North Atlantic, it has been demonstrated that phosphate depletion has a limiting effect when the concentration falls below about 0.5 mg.-at. of P per m³ (Riley, Stommel and Bumpus, 1949). Severe nitrogen depletion also reduces photosynthesis and growth, but the quantitative relationship has not been worked out adequately. At this point, a few physiological experiments with the Husan plankton would have helped the analysis. Lacking them, it is possible only to make what seem like reasonable assumptions about nutrient effects and then test them statistically. By a process of trial and error, various combinations of assumptions about phosphate and nitrate effects were fitted into the general plankton equation (the remainder of which will be described in due course) and statistically compared

with observed plankton changes. Since the only criterion was empirical agreement, and since the whole procedure was somewhat complicated, there is no assurance that the results are entirely correct. However, they are more or less in accord with experimental data obtained elsewhere. By these methods it was found that a likely nutrient effect was: (a) a reduction of photosynthesis proportional to phosphate depletion when the latter fell below 0.3 mg.-at. of P per m^3 (for example, with a concentration of 0.15 mg.-at., the photosynthetic rate would be 50% of the maximum permitted by physical conditions prevailing at the moment); (b) reduction of photosynthesis to zero with zero nitrate concentration, but otherwise no effect. In the middle graph in Fig. 4, the broken curve shows reductions from the basic radiation curve, indicating the decrease in potential photosynthesis that results from depletion of either phosphate or nitrate. From January to May 1932 there were no nitrate observations, and reductions during this period, based on phosphate alone, are shown as a dotted line.

Temperature affects nearly every physiological process. Its simplest manifestation is an approximate doubling of the rate of any given process with a ten-degree increase in temperature, so that the rate r_T of any process at temperature T is expressed by

$$r_T = r_o\, e^{.069T} ,$$

in which r_o is the rate at 0° C. This is a great over-simplification of the real situation, but the empirical method does not permit greater refinement. The lower part of Fig. 4 shows this basic temperature effect ($e^{.069T}$), which can be used in various ways in the equation. The best statistical agreement was obtained by using the temperature coefficient as an estimate of relative changes in phytoplankton respiration and also by including it with the other factors involved in photosynthesis.[2] There was no evidence that the grazing factor was improved by postulating a temperature effect.

The net result of the investigation at this point is the hypothesis that each of the physiological coefficients in equations (1) to (3) is proportional to certain measured factors in the environment. Thus the photosynthetic coefficient is expressed by

$$P_h \backsimeq \frac{I_o}{7.7K}\,(1 - e^{-7.7K})\; N \,.\, e^{.069T} ,$$

[2] Previous studies of this type (Riley, 1946, 1947) have not utilized a photosynthetic temperature coefficient, but examination of broad, regional variations in the oxygen production of surface phytoplankton (Riley, Stommel and Bumpus, 1949) indicates that temperature is an important factor and ought to be included.

in which N is the nutrient effect described above; the other factors have already been specifically identified. The phytoplankton respiratory coefficient is assessed in terms of temperature,

$$R \backsimeq e^{.069T} ,$$

and it is reasonable to suppose that the grazing coefficient varies with the size of the zooplankton population Z:

$$G \backsimeq Z .$$

Therefore it should be possible with appropriate constants to combine all the factors into an equation that would express their net effect on the rate of phytoplankton growth. In developing these constants, there are the alternatives (a) to depend entirely on statistical fitting, or (b) to use the same constants that were developed in the theoretical analyses of other areas. The second alternative was chosen since it seemed to be of some interest to determine the degree of general applicability of physiological constants; however, it so happens that both methods lead to nearly the same results. Two corrections in the numerical values of constants were necessitated by differences in method. First, the inclusion of a temperature factor in photosynthesis must be allowed for. Thus the previous photosynthetic constant, with a numerical value of 2.5, was divided by the mean value of $e^{.069T}$, and the new value became 0.85. Second, zooplankton had been rated previously in terms of volume, and it now becomes necessary to express the factor as numbers of organisms. A statistical analysis of Kokubo's data on numbers of zooplankton and volume of total plankton was used to establish an average conversion factor.

Equation (3), rewritten in terms of environmental factors, can now be stated

$$ln \frac{P_t}{P_o} = \frac{0.85\, I_o}{7.7K} (I - e^{-7.7K}) N . e^{.069T} - 0.0175e^{.069T} - 0.000136Z ,$$

in which the ratio $\frac{P_t}{P_o}$ represents the relative change in the population during a period of one day. On the basis of this equation it is now possible to construct a theoretical population curve by applying it to the observed numerical values of the various environmental factors, integrating successive short intervals (two-week periods) through the two years' observations. When this was done it was found that one additional factor must be taken into account. Instead of maintaining the same general level, the theoretical population at the end of

two years was much larger than it had been in the beginning. It was apparent that either the theoretical photosynthetic coefficient was too high, or some factor not properly accounted for was reducing the population. Statistical analyses indicated that the first alternative probably was not correct. Instead, realistic results were best obtained by subtracting a constant from the physiological terms, so that the equation became

$$ln \frac{P_t}{P_o} = \frac{0.85 I_o}{7.7K} (1 - e^{-7.7K}) N . e^{.069T} - 0.0175 e^{.069T} - 0.000136Z - 0.0393 . \quad (4)$$

Application of this equation yields relative population changes during the two-year period, and for comparison with the observed phytoplankton concentrations, the theoretical ratios can be converted to absolute concentrations by means of equation (2). The integration constant P_o is arbitrarily chosen. Hence, in the theoretical curve shown in Fig. 5, absolute concentrations have no fundamental meaning; it is only relative variations that are significant.

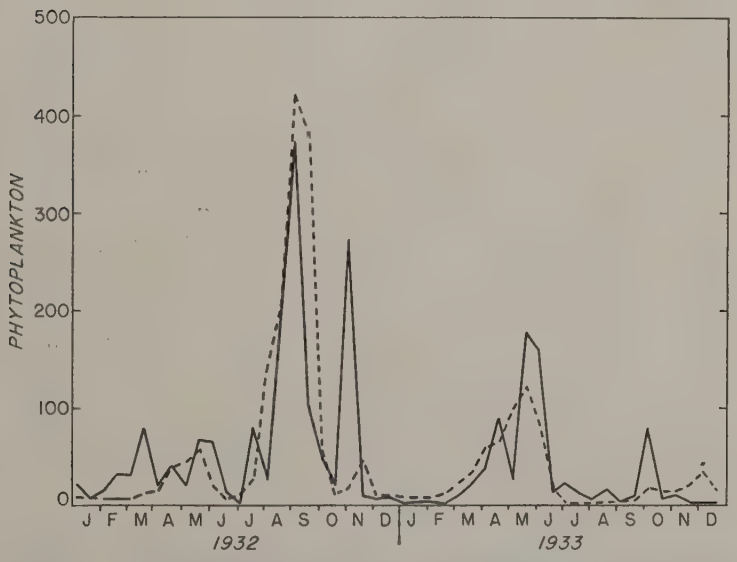

Figure 5. Phytoplankton, thousands of cells per liter. Solid line is the observed population. Broken line is a theoretical curve derived from environmental factors according to equations (2) and (4).

DISCUSSION

The agreement berween the observed and calculated populations in Fig. 5 is by no means perfect; however, it is apparent that the major objective has been accomplished, since the observed differences from one year to the next in the relative size of the populations and in the relative magnitude of individual flowerings are more or less preserved in the theoretical treatment. Therefore, by examining the environmental data step by step with respect to the way in which the component factors fit together in the equation, it becomes possible to discuss the environmental influences in the Husan area with a deeper insight into the principles of phytoplankton growth than would be possible simply by inspection of the primary data. The conclusions are summarized as follows:

The growth rate of the Husan plankton is higher, with any given complex of light, temperature, and nutrients, than in previous studies of other areas. This is indicated by the necessity of including a negative constant in the equation in order to make the cycle balance. There is a simple physical reason for this result. In shallow water, where the light intensity is adequate for growth from surface to bottom, the average growth rate is expected to be higher than in deeper water where some part of the population is always found below the compensation depth. The negative constant presumably means that the higher growth rate is balanced by a continual drain on the population by the outflow of water from Husan Harbor and by lateral mixing with the sparser populations of deeper water. It is an over-simplification of the facts to assume that such losses actually are constant, and undoubtedly better agreement could be obtained between observed and calculated populations if more were known about the hydrography of the region. The available data on the subject tend to support this contention. If the probable population loss is rated as the difference between theoretical and observed population changes during successive two-week periods, there is a small but significant correlation of the order of 0.2 between these values and the increase in the salinity of the water during the same periods. The salinity change is of course indicative, at least in part, of interchange with water of higher salinity off shore, but its value as a quantitative indicator of lateral mixing is considerably reduced by the fact that the salinity must also be affected by variations in the flow of river water into the harbor.

The seasonal fluctuation in the mean radiation in the water column is relatively smaller than that of incident radiation. This results from high transparency of the water in midwinter and lower values

in late spring and summer. Since these variations in transparency are correlated to a considerable degree with the size of the phytoplankton population, the latter can be said to behave in this respect as a self-regulating mechanism, reducing its growth rate as the population density increases and vice versa. Self-regulatory mechanisms probably also exist in the relations of phytoplankton with nutrients and zooplankton. Thus seasonal fluctuation in growth coefficients seem to be less than that of the basic physical factors.

Each major flowering is accompanied by nutrient depletion (phosphate, nitrate, or both), and this is the chief factor responsible for its termination. The length and severity of the depletion is correlated with the size of the preceding flowering and is also reflected in the extent of the population decline and the time required for the population to recover and produce the next flowering. The net result is that a large summer flowering tends to occur after a small spring one and vice versa.

While nutrients appear to be the most important factors to be considered in connection with summer flowerings, it is apparent that every other factor also contributed to produce the great difference between the summer-autumn flowerings of 1932 and 1933. In 1932 the nutrients recovered in late June, so that a flowering was possible any time thereafter, and during the next month the effective radiation was greater than it was during the analogous recovery period of 1933, which began in late July. During these periods of potential augmentation, the temperature and the quantity of zooplankton were less in 1932, so that there was less opportunity for the dissipation of organic matter by respiration and grazing.

During the period from late autumn to early spring, the adverse influences of the summer—nutrient depletion, respiration, grazing—were reduced to a minimum. As far as the theoretical analysis is concerned, the difference in the spring flowerings of 1932 and 1933 was the result of rather small differences in the magnitude and duration of the spring radiation pulses, and the midwinter minima were caused by low radiation at that season. Admittedly the theoretical curve is not a very good fit for this part of the data, and there must be important undescribed factors. In particular, it seems likely that the inshore population is very susceptible during the early stages of the spring flowering to losses by lateral mixing with offshore water, where presumably the flowering begins later.

SUMMARY

1. Published data on the plankton of Husan Harbor, Korea and its environmental factors during 1932 and 1933 are used as the basis

for a theoretical investigation of the reasons for differences that occur from one year to the next in phytoplankton seasonal cycles.

2. The analysis utilizes methods previously developed for the study of other regions, with a few slight modifications necessitated by local conditions and by differences in methods of measurement. A simple differential equation is written, in which the rate of change of the phytoplankton population is described in terms of physiological processes that increase or decrease its organic content (photosynthesis, respiration, and grazing), and in which the rates of the individual processes are quantitatively assessed by reference to a few environmental factors—radiation, transparency, temperature, phosphate, nitrate, and the quantity of zooplankton. Application of these factors to the equation results in a theoretical phytoplankton curve that is essentially in agreement with observed phytoplankton concentrations.

3. Nutrient salts appear to be the most important factors determining the time, duration, and relative magnitude of summer and autumn flowerings, although all the other factors have some influence. The midwinter minima and spring flowerings seem to be controlled primarily by radiation.

4. Marked differences in seasonal cycles from one year to the next are depicted with sufficient accuracy by the theoretical curves to leave little doubt that they are largely caused by variations in the factors listed.

REFERENCES

Kimball, H. H.

1928. Amount of solar radiation that reaches the earth on the land and on the sea, and methods by which it is measured. Mon. Weath. Rev. Wash., *56:* 393–398.

Kokubo, Seiji

1940. Quantitative studies of the neritic littoral microplankton of Japan collected at sixteen stations ranging from Saghalien to Formosa 1931–1933. Proc. Sixth Pac. Sci. Cong., Calif. (1939), *3:* 541–564.

Riley, G. A.

1946. Factors controlling phytoplankton populations on Georges Bank. J. Mar. Res., *6:* 54–73.

1947. Seasonal fluctuations of the phytoplankton population in New England coastal waters. J. Mar. Res., *6:* 114–125.

Riley, G. A., Henry Stommel and D. F. Bumpus

1949. Quantitative ecology of the plankton of the western North Atlantic. Bull. Bingham Oceanogr. Coll., *12* (3). In press.

Contribution No. 473

Reprinted from the JOURNAL OF CELLULAR AND COMPARATIVE PHYSIOLOGY
Vol. 33, No. 3, June, 1949

THE GROWTH AND OPTIMUM YIELDS OF UNICELLULAR ALGAE IN MASS CULTURE[1]

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THREE FIGURES

INTRODUCTION

Various Chlorophyceae have been grown in mass culture with a view to selecting species suitable for production in quantity, and to learning the most advantageous conditions for their growth. The culture technique described by Ketchum and Redfield ('38) has been modified to permit maintenance of the cultures under more nearly sterile conditions.

The object of mass culture is to obtain material of sufficient purity and quantity for physiological investigation and chemical analysis. The question of when and how to harvest is of importance if optimum yields are to be obtained. Ketchum and Redfield ('38) applied "the theory of the optimum catch" of Hjort, Jahn and Ottestad ('33) in harvesting Nitzschia cultures. In brief, the theory of the optimum catch states that every population has an optimum density for the production of new individuals. If the population is too dense, competition or other adverse factors limit the multiplication rate so that fewer surviving individuals are produced. In a small population, even though the multiplication rate may be large, only a small number of new individuals can

[1] Contribution No. 473 from The Woods Hole Oceanographic Institution, aided by a grant from the Carnegie Corporation.

be produced because of the small parent stock. It follows that the maximum harvest can be made at that level where the product of the multiplication rate times the size of the population is at a maximum. If the harvesting rate is kept within the limits of the capacity of the population to reproduce, the population will approach a concentration where its multiplication rate just balances the rate of harvest. If the harvesting rate is excessive, the population will approach extinction.

The theory of the optimum catch is, however, merely a deduction from the form of the normal growth curve of a population, and has not to our knowledge been put to practical test. We have, consequently, made a number of experiments to determine whether it is a reliable guide to harvesting, and to establish the most practical way of handling a culture with the object of obtaining a continuous maximal yield.

METHODS

The cultures were grown by the method described by Ketchum and Redfield ('38) as modified by Scott ('43). A pyrex bottle containing 8 liters of culture was illuminated by a specially constructed neon tube in a water jacket placed in the axis of the bottle. The mouth of the bottle around the water jacket was packed with cotton. Air containing 5% CO_2 was bubbled through the culture to maintain a uniform CO_2 pressure and to keep the cells in suspension. This gas was bubbled first through a long tube, stuffed with cotton, and then through a water trap. Samples were withdrawn and fresh media added through a siphon. The necessary glass tubes were packed in the cotton in the neck of the bottle. The entire culture flask, with all of these tubes except the neon tube in place, was autoclaved at 15 lb. pressure for 45 minutes. The cultures discussed were pure, and free of bacterial contamination.

Detmer's culture medium of the following composition was used:

$Ca(NO_3)_2$	1.00 gram
$Mg\ SO_4$	0.25 gram
KCl	0.25 gram
KH_2PO_4	0.25 gram
$FeCl_3$	0.01 gram

Distilled water to make 1000 ml

Cell counts were made with a hemocytometer

To determine the dry weight of the cells produced a liter of culture was centrifuged for half an hour at approximately 2500 RPM. The supernatant was poured off and the cells were resuspended in distilled water, transferred to 100 cm^3 centrifuge tubes, and again centrifuged out. The cells were then transferred with very little water to aluminum dishes and placed in a vacuum dessicator over $CaCl_2$ or H_2SO_4. The pressure was reduced to about 18 mm of mercury for about two hours. This treatment removes the dissolved gases in the water and prevents spattering. The pressure was then reduced to the capacity of a Hivac pump. The material became practically dry in a few hours, and dried to constant weight in 18–24 hours. The material was then ground to a fine powder, and stored in small, tightly stoppered vials.

Population growth and theoretical yields

The normal growth of a population is characterized by an initial lag period, a period of logarithmic increase during which the rate of increase of the population is proportional to its size, and a period of declining multiplication rate when growth is limited by competition or other factors. The average growth curve of three cultures of *Stichococcus bacillaris* is given in figure 1. The individual counts show considerable variation from the average at the high and low cell concentrations, but are more consistent at intermediate concentrations.

The division rate of these cultures increased at first from a low value, characterizing the initial lag period, to a briefly

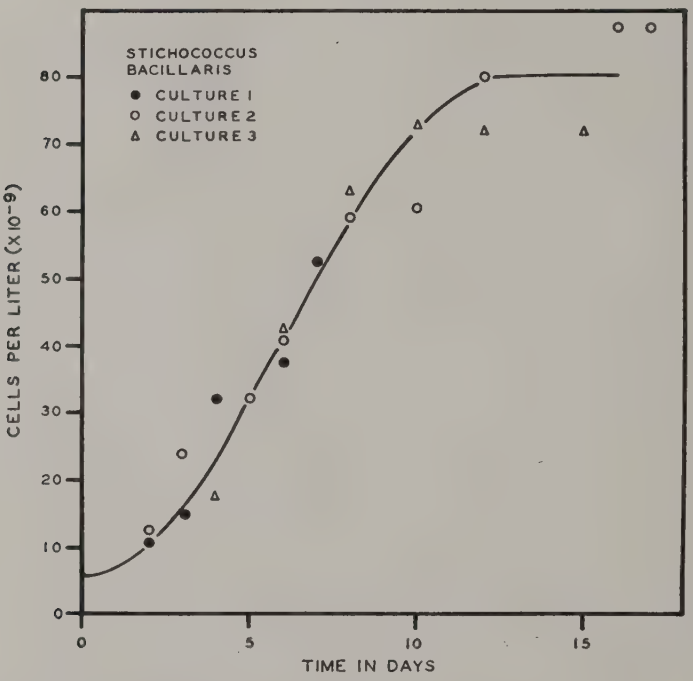

Fig. 1 The average growth of three cultures of *Stichococcus bacillaris* in 8 liter mass cultures.

maintained maximum value, and then declined progressively throughout the remainder of the growth period. The division rate, k, is obtained from the equation

$$\ln \frac{C_2}{C_1} = k(t_2 - t_1)$$

in which C_2 and C_1 are respectively the cell concentrations at the end and beginning of the time period under consideration, $(t_2 - t_1)$. The values for the division rates, calculated from the average curve of figure 1, are plotted against the cell concentration in figure 2.

The total daily production of cells, or yield, of the culture is also compared to the size of the population in figure 2. The yield is, of course, a function of both the total cell count and of the rate of cell multiplication. If the latter remained constant, greater yields would be obtained the

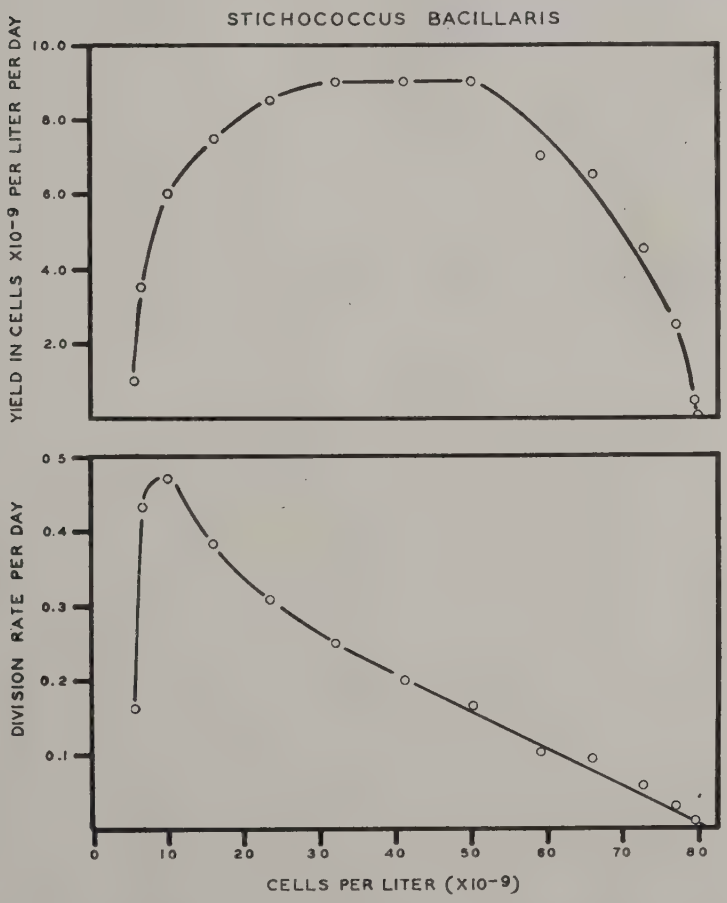

Fig. 2 The yield, in cells per liter, and the division rate per day of *Stichococcus bacillaris* cultures at different population densities.

greater the population. Under the conditions obtaining in our culture method, the yield first increased as the cell concentration increased. Between about 30 and 50×10^9 cells per liter, a uniform, maximum yield of 9×10^9 cells per liter per day was obtained. The total production of the culture then decreased gradually, in spite of increasing cell concentrations, as the multiplication rate decreased. Both the division rate and yield were zero at a cell concentration of about 80×10^9 cells per liter.

The theoretical maximum yield from the *Stichococcus* culture under these conditions is, therefore, about 9×10^9 cells per liter per day, and this yield may be expected whenever the cell count lies between 30 and 50×10^9 cells per liter. It remains to be determined whether such a yield can be repeatedly obtained from the same culture by removing a portion of the culture at intervals and replacing the harvest with an equivalent volume of culture solution.

Yields of Stichococcus bacillaris cultures

We have chosen for examination a system in which one-half the culture is harvested periodically. Under this regimen, the interval between harvests must be sufficient to allow the cells to double in number. During the period of most rapid growth, the cultures of *Stichococcus bacillaris* doubled in about a day and a half. Removal of half of the culture requires longer growth periods than this or the culture will approach extinction.

The intervals between harvests and the appropriate densities of populations can be determined graphically from the growth curve. The density of population at which one should start if the numbers are to double during time intervals of two, three, 4 and 6 days and the daily yields predicted from the growth curve for each interval are shown in table 1. These predictions are somewhat lower than those shown in figure 2 for equivalent cell concentrations. This results because the population is allowed to grow between

definite limits of density, rather than be maintained constantly at one density.

To test these predictions in actual practice, cultures of *Stichococcus bacillaris* were maintained at appropriate levels and one-half was harvested every two, three, 4 and 6 days. Daily yields were estimated not only by cell count, but by weighing aliquots of the dried product. The data for the individual harvests are recorded in table 2, and the mean yields under each regimen are included in table 1. The experiments show that the cultures may be maintained during successive harvests at a uniform range of concentration close to that predicted from the growth curve. The cultures

TABLE 1

Theoretical and actual yields of Stichococcus bacillaris cultures under a regimen of harvesting one-half the culture at various intervals

INTERVAL	CELL COUNT		THEORETICAL YIELD PER LITER PER DAY	ACTUAL YIELD PER LITER PER DAY
	Initial	Final		
days	*cells/liter*	*cells/liter*	*cells*	*cells*
2	5×10^6	10×10^6	2.5×10^6	3.31×10^6
3	26×10^6	52×10^6	8.6×10^6	6.71×10^6
4	33×10^6	66×10^6	8.3×10^6	7.28×10^6
6	39×10^6	78×10^6	6.5×10^6	6.60×10^6

maintained on a two-day schedule of harvest varied from period to period more than those cultured for longer times at higher cell concentrations. On the two-day schedule, the division rates were generally greater than those observed in the freshly inoculated culture, and, as a result, the counts tended to increase with successive harvests. Presumably the cells become adapted to the conditions of culture, and the physiological properties which result in low rates of multiplication in a fresh culture (i.e., the lag period) are not present under these conditions. The yield obtained when half the culture was harvested every two days is consequently somewhat greater than that predicted from the growth curve. In contrast, the yields under the three- and 4-day regi-

TABLE 2

Yield of Stichococcus bacillaris cultures. Eight-liter cultures; harvested 4 liters at various intervals as shown

HARVEST INTERVAL	CELL COUNT		YIELD PER LITER PER DAY [a]		MEAN YIELD	MEAN YIELD
	Initial	Final				
days	*cells/liter*	*cells/liter*	*cells*	*gm*	*cells*	*gm*
2	5.0×10^9	12.0×10^9	3.0×10^9	0.0268		
2	6.0×10^9	18.0×10^9	4.5×10^9	0.0298		
2	4.8×10^9	11.4×10^9	2.85×10^9	0.0202		
2	5.7×10^9	11.0×10^9	2.75×10^9	0.0220		
2	5.5×10^9	15.0×10^9	3.75×10^9	0.0185		
2	7.5×10^9	8.0×10^9	2.00×10^9	0.0157		
2	4.0×10^9	14.0×10^9	3.50×10^9	0.0307		
2	7.0×10^9	15.8×10^9	3.95×10^9	0.0170		
2	7.9×10^9	14.0×10^9	3.50×10^9	.....	3.31×10^9	0.0226
3	25.0×10^9	39.2×10^9	6.55×10^9	0.0368		
3	19.6×10^9	38.3×10^9	6.39×10^9	0.0376		
3	19.1×10^9	39.0×10^9	6.50×10^9	0.0447		
3	19.5×10^9	44.5×10^9	7.42×10^9	0.0446	6.71×10^9	0.0409
4	30.0×10^9	58.0×10^9	7.25×10^9	0.0390		
4	29.0×10^9	54.0×10^9	6.75×10^9	0.0366		
4	27.0×10^9	59.0×10^9	7.39×10^9	0.0416		
4	29.5×10^9	61.0×10^9	7.62×10^9	0.0421		
4	30.5×10^9	59.0×10^9	7.39×10^9	0.0360	7.28×10^9	0.0391
6	37.5×10^9	82.0×10^9	6.83×10^9	0.0392		
6	41.0×10^9	79.0×10^9	6.56×10^9	.....		
6	39.5×10^9	77.0×10^9	6.42×10^9	.....	6.60×10^9	0.0392

[a] $\frac{\text{liters harvested} \times \text{final cell count}}{\text{volume of culture} \times \text{days' growth}}$

mens are smaller than the predicted yields. The yield of cells is maximal for the 4-day schedule of harvest.

The yield of the culture was also measured by determining the dry weight of an aliquot of the harvest. Like the cell counts, the daily yield of dry material varies somewhat from period to period. The average values for each regimen are very nearly the same, except for the two-day period. Evidently there is no advantage to be gained by selecting between the three-, 4- and 6-day periods, all of which give a daily yield of about 40 mg/liter. For the 8-liter culture somewhat more than 300 mg of dry cell material per day is obtained under these culture conditions.

These experiments indicate that much reliance may be placed on the growth curve in predicting the yields to be obtained under various systems of harvest. Practical considerations will determine the regimen to be adopted. Thus, if a moderate number of fresh cells are required for experimentation, it may be wise to keep a culture at high concentration and harvest a small fraction at short intervals, since the labor of separating a given quantity of cells from the solution by centrifuging will be less if they are concentrated. To obtain the largest possible supply of cells under routine conditions, it will be advantageous, in order to reduce the labor of harvesting, to use the longest interval compatible with efficient growth. The growth curve of *Stichococcus bacillaris* (fig. 1) is nearly linear between the concentrations of 20×10^9 and 70×10^9 cells per liter. Seven days are required for this growth. This rate of cell production, 7.14×10^9 cells per liter per day, is nearly as great as the maximum yields which can be obtained. We have consequently adopted for the practical culture of this species a regimen in which sufficient culture is harvested each week to reduce the stock to 20×10^9 cells per liter. The yields from two successive harvests under these conditions are given in table 3. The daily yield under these conditions is not inferior to those of the various regimens in table 2.

TABLE 3

Yield of Stichococcus bacillaris culture harvested at 7-day intervals starting with concentration of 20 × 10⁹ cells per liter. Eight-liter culture; harvested 5.66 liters per week

HARVEST INTERVAL	CELL COUNT		YIELD PER LITER PER DAY	YIELD PER LITER PER DAY
	Initial	Final		
days	*cells/liter*	*cells/liter*	*cells*	*gm*
7	20×10^9	67.5×10^9	6.83×10^9	0.0409
7	20×10^9	69.2×10^9	7.00×10^9	0.0433

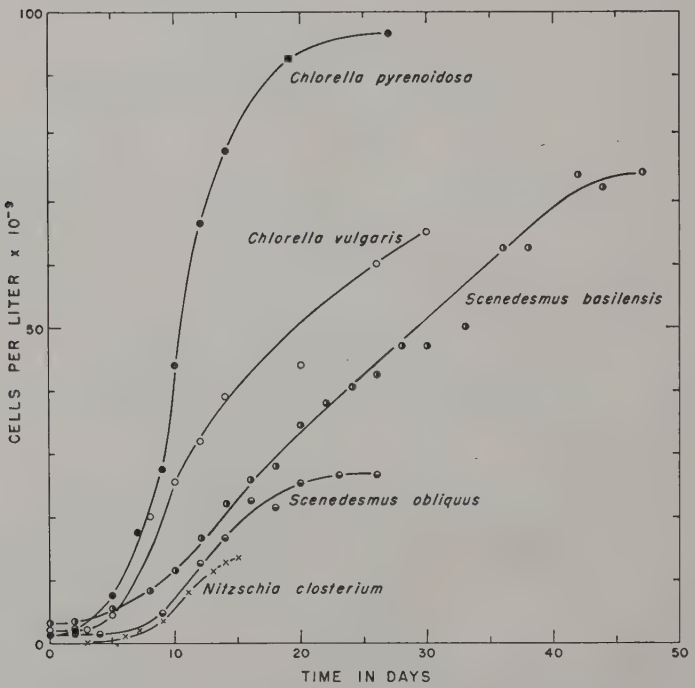

Fig. 3 The growth curves of various algae in 8 liter mass cultures.

The growth curves of various species

In addition to *Stichococcus bacillaris,* we have reared *Chlorella pyrenoidosa, C. vulgaris, Scenedesmus basilensis,* and *S. obliquus* in mass cultures. The growth curves for these cultures are illustrated in figure 3. The growth curve

TABLE 4

The yield of mass cultures of various algae, grown for 7-day intervals, as predicted from their growth curves

SPECIES	CELL COUNT		YIELD PER LITER PER DAY	MEAN WEIGHT PER CELL	YIELD PER LITER PER DAY
	Initial	Final			
	cells/liter	*cells/liter*	*cells*	*gm*	*gm*
Stichococcus bacillaris	20×10^9	70×10^9	7.14×10^9	$0.60^a \times 10^{-11}$	0.043
Chlorella pyrenoidosa	16×10^9	78×10^9	8.86×10^9	$0.742^b \times 10^{-11}$	0.065
Chlorella vulgaris	5×10^9	32×10^9	3.86×10^9	$1.07^c \times 10^{-11}$	0.041
Scenedesmus obliquus no. 1	5×10^9	18×10^9	1.86×10^9	$1.46^c \times 10^{-11}$	0.027
Scenedesmus obliquus no. 2	5×10^9	23×10^9	2.57×10^9	$1.64^c \times 10^{-11}$	0.042
Scenedesmus basilensis	20×10^9	35×10^9	2.14×10^9	$1.41^c \times 10^{-11}$	0.030
Nitzschia Closterium	1.8×10^9	12.8×10^9	1.57×10^9	$2.32^c \times 10^{-11}$	0.036

[a] Based on 16 analyses; cell densities at time of analysis ranged from 36–70 $\times$ 10^9 cells per liter.

[b] Based on 7 analyses; cell densities at time of analysis ranged from 37–98 $\times$ 10^9 cells per liter.

[c] Based on a single analysis of a dense culture.

of *Nitzschia Closterium,* measured by Ketchum and Redfield ('38), is also presented. From these curves the expected yield on a 7-day schedule of harvest has been deduced by selecting the portion of the curve over which the greatest increase occurs in that time. In table 4 the initial and final

densities of population indicated for such a regimen are entered together with the predicted daily yields.

Chlorella pyrenoidosa and *Stichococcus bacillaris* appear greatly superior to the other species in the yield of cells. The yield in weight, however, is more significant than the cell count for determining production of cell substances. The mean dry weight per cell of the various species has been determined and used as a factor to estimate the daily yield in grams. The results entered in table 4 show that, in terms of weight, the rate of production varies less than two and one-half-fold in contrast to the almost sixfold variation in production of cells. *Chlorella pyrenoidosa* emerges as superior to the other species with either method of measurement. *Stichococcus bacillaris*, however, produces a weight no greater than some of the other species which produce far fewer members of cells.

It appears from these results that the rate of assimilation and production of new cell substance is nearly the same, even for species of very different size. The factors which inhibit growth and multiplication under these culture conditions affect the larger species at lower cell concentrations. Cell counts alone, therefore, suggest an illusory superiority for the smaller species. It is surprising that such a variety of species carries on assimilation at so nearly the same rate within the limits set by our culture techniques. A further study of the relative rates of assimilation of various species under more exactly controlled conditions is desirable.

SUMMARY

1. Five Chlorophyceae *(Stichococcus bacillaris, Chlorella pyrenoidosa, C. vulgaris, Scenedesmus obliquus, S. basilensis)* and one marine diatom *(Nitzschia Closterium)* have been grown in mass culture and their growth curves are presented.

2. The optimum yield has been deduced from the growth curve of *Stichococcus bacillaris*. This is compared with the yields obtained by harvesting half of the culture every two,

three, 4 and 6 days and that obtained by harvesting a larger proportion of the culture weekly.

3. Under the two-day regimen the multiplication rates are somewhat higher than in the normal growth curve, and the population tends to increase with successive harvests. Presumably, the cells become adapted to the conditions of culture and the lag period observed in fresh cultures does not persist during the successive harvests.

4. The yields under the other schedules of harvest do not differ significantly from one another, and indicate that a yield of about 7×10^9 cells per liter per day can be obtained. The dry weight of this production is about 300 mg daily for the 8-liter culture.

5. The results indicate that the yields predicted from the growth curves can be obtained consistently with various systems of harvest. The general concepts of the theory of the optimum catch are thus confirmed experimentally.

6. The yield in cells and in dry weight for the species listed above has been deduced from their growth curves and from the mean weight per cell. *Chlorella pyrenoidosa* emerges as somewhat superior to the others. Though the smaller species give greater numbers of cells, the weight produced is nearly the same for all species, indicating that all carry on assimilation at nearly the same rate under the conditions of culture.

LITERATURE CITED

HJORT, JOHAN, GUNNER JAHN AND PER OTTESTAD 1933 Essays on population: the optimum catch. Hvalrådets Skriffter, *7:* 92–127.

KETCHUM, BOSTWICK H. AND ALFRED C. REDFIELD 1938 A method for maintaining a continuous supply of marine diatoms by culture. Biol. Bull., *75* (1): 165–169.

SCOTT, G. TAYLOR 1943 The mineral composition of *Chlorella pyrenoidosa* grown in culture media containing varying concentrations of calcium, magnesium, potassium, and sodium. J. Cell. and Comp. Physiol., *21* (3): 327–338.

Contribution No. 474

Reprinted from the JOURNAL OF CELLULAR AND COMPARATIVE PHYSIOLOGY
Vol. 33, No. 3, June, 1949

SOME PHYSICAL AND CHEMICAL CHARACTERISTICS OF ALGAE GROWTH IN MASS CULTURE [1]

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TWO FIGURES

INTRODUCTION

Some physical and chemical properties of various Chlorophyceae have been measured in order to determine whether different species have an inherent tendency to contain similar proportions of essential elements when grown under a given set of environmental conditions. Natural collections of algal plankton are similar in their composition (Redfield, '34; Fleming, '40). This similarity may depend either upon similarity of environment or upon an inherent uniformity among the different species in the population. The relative importance of these influences has not been fully assessed.

It has been shown that the composition of some algae can be varied by growing them in media deficient in various elements. Thus, Franzew ('32), Ketchum ('39) and Rodhe ('48) have demonstrated that various algae are able to continue to grow and produce new cell substance in the absence of phosphorus and nitrogen in the culture medium. The species used in these studies were *Nitzschia Closterium, Chlorella pyrenoidosa, Scenedesmus quadricauda* and *Pandorina Morum.* Scott ('43) has similarly produced variations in the potassium, sodium, calcium and magnesium con-

[1] Contribution No. 474 from The Woods Hole Oceanographic Institution, aided by a grant from The Carnegie Corporation.

tent of *Chlorella pyrenoidosa* and Haskins ('41) has demonstrated variations in the chlorophyll and carotenoid content of this species grown in media deficient in nitrogen and magnesium. These variations in mineral constituents of the cells must be associated with variations in the proportions of protein, carbohydrate and fat in the cells. Spoehr and Milner ('49) have demonstrated such variations in *Chlorella pyrenoidosa* as the result of growth under various experimental conditions. It is apparent, therefore, that the composition of algae can be changed experimentally by growing them in media deficient in various elements.

Five species of Chlorophyceae and a marine diatom have been grown in sufficient quantities in culture under a given set of conditions to permit determination of the weight, volume and proportions of carbon, nitrogen, hydrogen, oxygen, phosphorus and ash in the cells. The results are presented in this paper. The changes which take place in *Chlorella pyrenoidosa* during the development and restoration of deficiencies of nitrogen and phosphorus are also described.

METHODS

The cultures were grown by the method described by Ketchum, Lillick and Redfield ('49). The cells were separated by centrifuging, and were dried in vacuo to constant weight. Cell counts were made with a hemocytometer. The volume measurements were made in Goetz Phosphorus Tubes. These tubes, containing 100 ml of the culture, were centrifuged at 2000 RPM for 30 minutes. The cells were measured in a capillary, 30 mm of which contained 0.2 ml, calibrated at intervals of 0.01 ml. The centrifugal force was 3.7×10^8 dynes or 3.78×10^5 times gravity, which gave constant and reproducible volume measurements.

Direct measurements of cell size were made by projecting the image of the cells on a screen by means of a 90° prism on a microscope. The degree of magnification was determined by measuring the projected size of the squares of the hemocytometer.

Analytical methods

1. Sampling. The vacuum dried sample was ground to a fine powder in a mortar. Approximately the correct amount of the dried material was placed in a platinum boat, dried at 105°C. for one and a half hours, and weighed. Except for the carbon analysis, the sample was then transferred to the correct container, and the boat and any adhering residue reweighed.

2. Carbon, hydrogen, oxygen and ash. A semi-micro modification of Pregl's microcombustion method as described by Fieser ('35) has been used with a sample of 40–50 mg of the dry material. The filling of the combustion tube was that given by Pregl ('35). The carbon was absorbed by ascarite as CO_2, the hydrogen by dehydrite as H_2O, and weighed. The ash remaining after the combustion was also weighed. The oxygen was calculated as the difference between the sum of the carbon, hydrogen, nitrogen and ash, and the weight of the sample.

3. Nitrogen. A sample of 10–15 mg of dry material was oxidized in a 100 ml Kjeldahl flask by the method described by Pregl ('30). The ammonia formed was distilled in a Parnas and Wagner still into an accurately measured volume of CO_2 free 0.01 N HCl, to which a small amount of methyl red was added. This was titrated with CO_2 free 0.01 N NaOH. The solution was boiled vigorously just before the end point to remove CO_2.

4. Phosphorus. A sample of 10–15 mg of the dried material was oxidized in a 125 ml Erlenmeyer flask by the method described by. Redfield, Smith and Ketchum ('37). After appropriate dilution, enough acid to bring the final concentration equivalent to 2 ml of 38% H_2SO_4 was added, followed by 2 ml of 2.5% ammonium molybdate and two drops of a solution containing 2.5 gr of $SnCl_2 \cdot 2H_2O$ in 100 ml of 10% (by volume) HCl. The color developed was read in a Pulfrich photometer using filter No. S.–72. The compensating cell was filled with distilled water plus reagents to compensate for reagent blank.

THE PHYSICAL CHARACTERISTICS OF VARIOUS SPECIES

In making routine counts of algae, the observer is constantly struck by the variation in the size of the cells of a culture as a whole. On one day he may record "cells very small," on another "cells large." Such impressions are given quantitative objectivity by measurements of cell

TABLE 1

Weight and volume of cells of various algae grown in cultures

SPECIES	CELLS PER LITER	DRY WEIGHT PER CELL	VOLUME PER CELL	DRY WEIGHT PER VOLUME
	cells	*gm*	cm^3	gm/cm^3
Stichococcus bacillaris	18.2×10^9	0.655×10^{-11}		
	39.0×10^9	0.687×10^{-11}		
	61.0×10^9	0.552×10^{-11}	2.44×10^{-11}	0.226
	69.0×10^9	0.602×10^{-11}	2.44×10^{-11}	0.247
	74.0×10^9	0.915×10^{-11}		
	130.0×10^9	0.778×10^{-11}	2.60×10^{-11}	0.299
Ave.		0.681×10^{-11}	2.49×10^{-11}	0.257
St. Dev.		0.095×10^{-11}	...	....
Chlorella pyrenoidosa	36.9×10^9	0.757×10^{-11}	3.25×10^{-11}	0.235
	38.1×10^9	0.574×10^{-11}		
	53.0×10^9	0.682×10^{-11}	3.40×10^{-11}	0.200
	56.0×10^9	0.756×10^{-11}		
	61.1×10^9	0.680×10^{-11}	3.22×10^{-11}	0.212
	63.2×10^9		4.86×10^{-11}	
	63.5×10^9	1.05×10^{-11}	4.66×10^{-11}	0.225
	75.8×10^9	0.706×10^{-11}	3.20×10^{-11}	0.221
Ave.		0.743×10^{-11}	3.76×10^{-11}	0.219
St. Dev.		0.075×10^{-11}	0.66×10^{-11}	0.010
Chlorella vulgaris	37.6×10^9	1.07×10^{-11}	4.98×10^{-11}	0.215
Scenedesmus obliquus no. 1	28.3×10^9	1.46×10^{-11}	5.94×10^{-11}	0.246
Scenedesmus obliquus no. 2	26.6×10^9	1.64×10^{-11}	8.27×10^{-11}	0.198
Scenedesmus basilensis	75.0×10^9	1.41×10^{-11}	5.68×10^{-11}	0.248
Nitzschia Closterium	20.0×10^9	2.32×10^{-11}		....

weight and cell volume. Table 1 gives the characteristics of cells of various cultures measured as dry weight and as centrifuged displacement volume. The cell counts, taken in connection with the growth curves presented by Ketchum, Lillick and Redfield ('49) serve to indicate the maturity of the culture. These figures are statistical averages for the population as a whole; the individual variations from the average will be discussed below.

In the *Stichococcus bacillaris* and *Chlorella pyrenoidosa* cultures, there was an almost twofold variation in the average size of the cells, but there was no consistent trend which would indicate a dependence of size upon the age or maturity of the culture. The ratio of weight to volume is of interest because it gives a close approximation to the percentage of solids in the cell. On the whole, this characteristic was less variable than either weight or volume, ranging from 0.198 to 0.299, i.e., 20–30% solids.

To show how the average size of the cells is related to the age of the culture, the results of dry weight measurements on 20 *Stichococcus* cultures are plotted against the cell count in figure 1. The mean weight per cell varies from 0.43 to 0.915×10^{-11} gm with a modal value of about 0.6×10^{-11} gm. The distribution of points indicates that the greatest variation occurs in the more dilute cultures, when division is most frequent. As shown in a previous paper the yield in weight of these dilute cultures is much less variable than the yield of cells.

These results indicate that conditions which are quite obscure may alter the relation between the division rate and the growth in size of the cells of the population, and suggest that the synthesis of new material proceeds with greater regularity than does the cycle of cell division. Because of this consideration, cell counts are not necessarily a precise index of the growth of the culture, and some of the irregularity in growth curves based on cell counts may be thus explained.

The values given above represent the statistical average of all of the cells in the population. Individual cells may vary greatly from this mean. To analyze this aspect of the problem, the diameters of the cells in *Chlorella pyrenoidosa* cultures have been measured. Samples of the cultures were placed in a counting chamber and projected optically onto a large sheet of paper. The outlines of 100 to 200 cells were

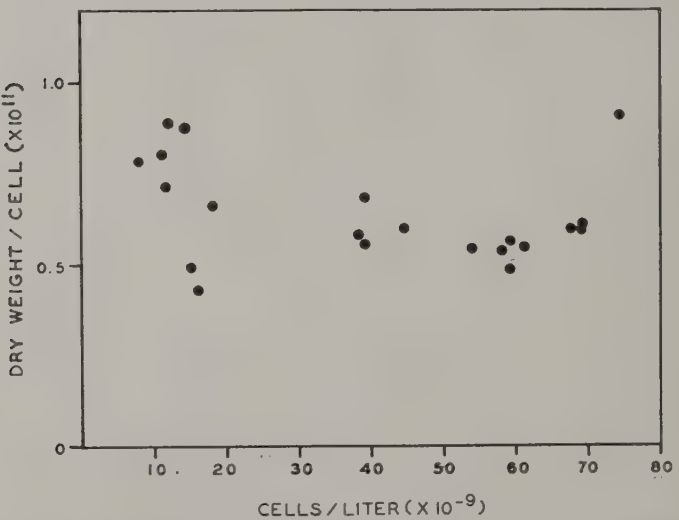

Fig. 1 The dry weight per cell of *Stichococcus bacillaris* grown in pure mass cultures as related to the cell count.

carefully traced on the paper and later the diameter was measured and grouped into size classes of 0.5 μ span. The percentage frequency polygons in figure 2 illustrate typical results for three different cell concentrations, as follows: A——6.0×10^9; B——53×10^9; C——97×10^9 cells per liter. These, and other similar determinations, show that the size distribution becomes more homogeneous as the culture becomes more mature. The diameter of the cells, for example, in the dilute, rapidly growing culture (2A) varied from 0.8

to 8.0 μ, corresponding to a 1000-fold range in volume. This is a much greater range than can be accounted for by the formation of autospores, of which *Chlorella* is said to produce 4, 8 and sometimes 16, so that it must be supposed

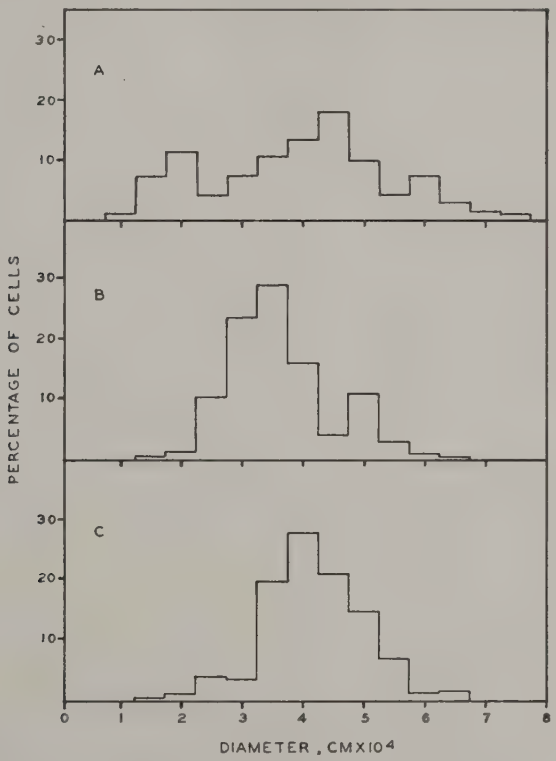

Fig. 2 The size distribution of cells in cultures of *Chlorella pyrenoidosa* at three diffierent cell concentrations as follows:
A, 6×10^6, B, 53×10^6 and C, 97×10^6 cells per liter.

that there is considerable variation in the size at which cell division takes place. In the culture illustrated in figure 2B, the diameters vary from 1.6–6.4 μ, corresponding to a 64-fold range in volume. A similar volume range (58-fold) is shown by the cells of the culture illustrated in figure 2C.

In this culture division had ceased at a cell concentration of 97×10^9 cells per liter.

The measurements of *Chlorella* populations amplify the observations of *Stichococcus* in showing that the cells of a culture may vary greatly in size from time to time and agree in suggesting that, as cell division slows down in the denser cultures, the medium-sized cell becomes the dominant member of the population. A more extensive series of observations is needed, however, to show under what conditions various types of size distribution in the population are to be expected.

ELEMENTARY CHEMICAL COMPOSITION OF VARIOUS SPECIES

The carbon, hydrogen, oxygen, nitrogen, phosphorus and ash content of various cultures has been determined, and the results are presented in table 2. There is a marked similarity in the content of carbon, hydrogen, oxygen and nitrogen in the various cultures. The phosphorus and ash content show greater variations. The different species differ no more than do various cultures of a single species, so that no significance can be attributed to specific differences. The *Chlorella pyrenoidosa* cultures are of very nearly the same composition regardless of the age and density of the culture. The more dense, older cultures of *Stichococcus,* however, differ from other cultures of this species in that they contain less carbon, hydrogen and nitrogen, and more phosphorus and ash. It may be significant that mature cultures of *Chlorella vulgaris, Scenedesmus obliquus, S. basilensis* and *Nitzschia Closterium* were used for these analyses, and the results resemble those obtained on the mature cultures of *Stichococcus.*

The weight proportions of carbon, nitrogen and phosphorus for these cultures are given in table 3. The ratio of carbon: nitrogen in these cultures is nearly identical for the various species and is very similar to that obtained for natural phytoplankton collections at sea (Redfield, '34, Fleming, '40). Thus, Redfield's values show an average ratio of carbon: nitrogen equal to 100: 13.5 by weight, the extremes being 100: 18

and 100:8.1. The present analyses of cultures of various species yield an average ratio of 100:13.6, the extreme values being 100:15.8 and 100:10.6.

The general agreement of the ratios as observed in natural collections and in pure cultures is of further interest since

TABLE 2

Elementary chemical analysis of various algae grown in cultures[1]

SPECIES	% DRY WEIGHT		% ASH-FREE DRY WEIGHT			
	Ash	P	C	H	N	O
Stichococcus	7.51	1.70	55.21	7.20	7.59	30.00
bacillaris	6.48	1.50	55.18	7.76	7.15	29.91
	7.31	1.69	55.45	7.67	6.86	30.02
	7.06	1.47	54.34	6.89	6.78	31.99
	17.21	3.43	51.62	6.39	5.95	36.04
	12.08	2.81	51.14	6 60	5.40	36.86
Ave.	9.61	2.10	53.82	7.09	6.62	32.47
St. dev.	3.36	0.68	1.63	0.46	0.63	2.65
Chlorella	10.98	2.69	54.24	7.47	7.46	30.83
pyrenoidosa	10.49	2.72	55.37	7.62	8.24	28.77
	14.02	2.83	56.02	7.90	6.94	29.14
	14.32	2.43	55.66	7.63	7.95	28.76
	10.50	2.52	54.84	7.52	7.51	30.13
	13.73	3.01	53.76	7.74	7.84	30.66
	11.01	2.75	54.73	7.70	8.15	29.42
	10.73	2.54	54.50	7.59	7.49	30.42
Ave.	11.93	2.69	54.89	7.64	7.70	29.77
St. dev.	1.53	0.14	0.60	0.10	0.35	0.74
Chlorella vulgaris	12.40	2.58	53.37	7.49	7.74	31.40
Scenedesmus obliquus no. 1	17.78	3.91	54.55	8.20	7.50	29.75
Scenedesmus obliquus no. 2	12.98	2.53	54.87	8.16	8.65	28.32
Scenedesmus basilensis	14.34	3.13	54.82	8.32	8.46	28.40
Nitzschia Closterium	19.52	1.03	54.98	7.49	6.67	30.86

[1] The arrangement of entries is the same as in table 1.

TABLE 3

Weight proportions of carbon, nitrogen and phosphorus, and the ash : phosphorus ratio in various algae grown in mass cultures

	C :	N :	P	ASH/P
Stichococcus	100	13.7	3.3	4.4
bacillaris	100	13.0	2.9	4.3
	100	12.4	3.3	4.3
	100	12.5	2.9	4.8
	100	11.5	8.0	5.0
	100	10.6	6.2	4.3
Average	100	12.3	4.4	4.5
Chlorella	100	13.8	5.6	4.1
pyrenoidosa	100	14.9	5.5	3.8
	100	12.4	5.9	4.9
	100	14.3	5.1	5.9
	100	13.7	5.1	4.2
	100	14.6	6.5	4.6
	100	14.9	5.6	4.0
	100	13.7	5.2	4.2
Average	100	14.1	5.6	4.4
Chlorella vulgaris	100	14.5	5.5	4.8
Scenedesmus obliquus no. 1	100	13.7	8.7	4.6
Scenedesmus obliquus no. 2	100	15.8	5.3	5.1
Scenedesmus basilensis	100	15.4	6.7	4.6
Nitzschia Closterium	100	12.1	2.3	19.0
Redfield sea water	100	16.7	2.44 [1]	..
Redfield phytoplankton	100	13.5	1.94	..

[1] Corrected for salt error as suggested by Cooper ('38).

the concentrations of the essential nutrients (CO_2 and NO_3^-) are much greater in the culture medium than they are commonly in natural bodies of water, particularly the sea. In spite of this, there is no indication that the chemical composition of the phytoplankton in the sea is influenced by the relative scarcity of these nutrients. It should be remembered, however, that collections of phytoplankton for analysis are commonly made at times when the nutrient conditions are favorable, since only then can sufficient quantities be readily obtained. It is not impossible that the cells living under the less favorable conditions which prevail much of the time may reflect this in their elementary composition.

The proportions of phosphorus and ash in the analyses shown in tables 2 and 3 are much more variable than are the carbon, hydrogen, and nitrogen. *Nitzschia* and *Stichococcus* appear to have relatively less phosphorus in the dry material than the other species. In the case of *Stichococcus,* however, the mature cultures contain more phosphorus than do the more actively growing cultures. It is not clear to what extent these variations in phosphorus content are to be explained as specific characteristics, particularly since it has been shown that great variations in phosphorus content may be occasioned by the availability of phosphate in the medium (Ketchum, '39). However, the culture medium used in these experiments contained twenty times as much phosphorus as was removed by the most densely populated Stichococcus culture.

The natural collections of diatoms and peridineans described by Redfield contained 1.94 gm of phosphorus for every 100 gm of carbon. In the cultures the average carbon : phosphorus ratio was 100 : 5.24; the extremes being 100 : 8.0 and 100 : 2.3. This may indicate that, under natural conditions, the phytoplankton are growing in a medium deficient in phosphorus but containing more adequate supplies of available nitrogen and carbon. Riley ('46, '47) has shown that phosphorus may at times limit the growth of phytoplankton in the sea.

The noteworthy feature of the ash analyses is that the quantity of ash is closely related to the amount of phosphorus in the cells. The ratio of ash to phosphorus in the various cultures recorded in table 3 varies between 5.89 : 1 and 4.3 : 1 and the general magnitude of the ratio is unchanged in spite of a threefold variation in the quantities present. This is about the ratio to be expected if the ash were a mixture of the pyrophosphates of K, Mg, and Ca. It appears, therefore, as though the ash of these unicellular algae is composed almost completely of phosphate salts and that the quantity of ash depends almost solely on the amount of phosphorus present. The specimen of *Nitzschia* is, of course, an exception, owing to the silicious shell which characterizes the diatoms.

ORGANIC CONSTITUENTS OF VARIOUS SPECIES

The degree of reduction and the proportions of protein, carbohydrate and fat have been estimated from the elementary analyses by the method described by Spoehr and Milner ('49). The degree of reduction, R value, is expressed as the percentage of the degree of reduction of methane, which has an R value of 100. Carbon dioxide, being fully oxidized, has an R value of zero. The general formula for the calculation of the R value, as given by Spoehr and Milner is

$$\text{R value} = \frac{[(\%C \times 2.664) + (\%H \times 7.936) - \%O] \times 100}{398.9}$$

in which C, H and O are the percentages of these elements based on the ash-free dry weight. The percent nitrogen multiplied by 6.25 gives the percent protein. From the R value and the percent protein one calculates the carbohydrate and lipid fraction by solution of the equations:

$$(\%P \times 42) + (\%C \times 28) + (\%L \times 67.5) = \text{R value} \times 100\%$$

and

$$\%P + \%C + \%L = 100$$

in which P, C and L stand for protein, carbohydrate and lipid respectively. The factors by which these are multiplied

in the equation are the R values of typical plant compounds as given by Spoehr and Milner.

The composition of the algae grown in cultures is presented in table 4. The R values range from 41.9–46.0 and all thus lie within the range given by Spoehr and Milner for *Chlorella pyrenoidosa.* The estimates of the proportions of protein,

TABLE 4

The degree of reduction and the proportions of protein, carbohydrate and lipids found in algae grown in mass cultures

SPECIES	R VALUE	PROTEIN	CARBOHYDRATE	LIPID
	%	%	%	%
Stichococcus bacillaris Ave. of *6*	41.9	41	38	21
Chlorella pyrenoidosa Ave. of *7*	44.5	48	27	25
Chlorella vulgaris	42.7	48	32	20
Scenedesmus obliquus no. 1	45.3	47	26	27
Scenedesmus obliquus no. 2	45.8	54	20	26
Scenedesmus basilensis	46.0	53	20	27
Nitzschia Closterium	43.9	42	33	25

carbohydrate and lipid are approximately the same for all species. This applies also to the diatom, *Nitzschia Closterium,* which contains these organic constituents in amounts which do not differ from the various species of Chlorophyceae.

EXPERIMENTAL VARIATIONS IN COMPOSITION

Cultures of *Chlorella pyrenoidosa* deficient in phosphorus or nitrogen have been produced by growing the cells in

media deficient in these elements. Some cultures were grown in tap water, where they were able to multiply threefold and develop cells deficient in both phosphorus and nitrogen. The cells deficient in nitrogen were produced in a medium in which the $Ca(NO_3)_2$ was replaced on an equimolar basis with $CaCl_2$. The cells deficient in phosphorus were grown in a medium in which the KH_2PO_4 was replaced by KCl. The elementary composition of the deficient cells is given in table 5.

TABLE 5

Elementary analysis of Chlorella pyrenoidosa deficient in nitrogen and phosphorus

DEFICIENT IN	% DRY WEIGHT		ASH/P	% ASH-FREE DRY WEIGHT			
	Ash	P		C	H	N	O
Nitrogen	5.25	1.08	4.9	53.77	6.51	3.20	36.52
and	5.51	0.96	5.7	58.14	8.34	2.54	30.98
phosphorus	7.03	0.91	7.7	55.10	7.78	5.20	31.92
Nitrogen	8.48	1.94	4.4	56.39	7.79	2.25	33.57
	9.04	1.69	5.4	55.33	8.78	2.72	33.17
				56.46	7.57	2.61	33.36
Phosphorus	4.41	0.59	7.5	53.73	8.02	8.70	29.55
	5.63	0.58	9.7	55.65	7.68	8.46	28.21
Recovery[1]							
In light	9.94	2.17	4.6	53.87	7.32	7.46	31.35
In dark	10.02	1.85	5.4	54.68	7.53	4.69	33.10
Normal							
Ave. table 2	11.93	2.69	4.4	54.89	7.64	7.70	29.77

[1] Culture deficient in nitrogen and phosphorus (first entry in table) to which 10 mg P, as KH_2PO_4, and 20 mg N, as KNO_3, were added per liter. Analyzed after recovery in the light or in the dark for 24 hours.

The phosphorus content of the cells grown in tap water was reduced to about one-third its normal content. The cells produced in the medium that was complete except for phosphorus, contained only about one-fifth the normal amount of phosphorus. This difference suggests that the growth in tap water was limited mainly by nitrogen, since, when nitrogen was available, greater deficiencies in phosphorus were de-

veloped. The ratio of ash to phosphorus in some of these deficient cells was substantially higher than in the normal cultures, ranging from 4.9 to 9.7.

The minimum nitrogen content of the cells grown in tap water was 2.54%, or about one-third the normal content. The deficiencies produced in media that were complete except for nitrogen were not substantially greater. This observation

TABLE 6

The degree of reduction and the proportions of protein, carbohydrates and lipids in Chlorella pyrenoidosa deficient in nitrogen and phosphorus

DEFICIENT IN	R VALUE	% ASH-FREE WEIGHT		
		Protein	Carbohydrate	Fat
Nitrogen	39.7	20	57	23
and	47.7	16	40	44
phosphorus	44.3	33	38	29
Nitrogen	44.7	14	49	37
	46.1	17	43	40
	46.9	16	42	42
Phosphorus	44.4	54	23	23
	45.4	53	22	25
Recovery [1]				
In light	42.7	47	32	21
In dark	43.2	29	43	28
Normal				
Ave. table 4	44.5	48	27	25

[1] See footnote table 5.

suggests again that nitrogen is the element limiting growth in these tap water experiments.

The composition of the organic matter in the deficient cultures has been estimated, as above, from their elementary analysis, and the results are presented in table 6. The normal *Chlorella pyrenoidosa* grown under these culture conditions was about half protein and contained approximately equal proportions of carbohydrate and fat. In most of the deficiency cultures the approximately equal proportions of

carbohydrate and fat persisted, even though the protein content was reduced greatly. In three experiments, however, the carbohydrate proportion was substantially greater than that of the fat. The cells in two of these were deficient in both phosphorus and nitrogen. The other was nearly normal in its phosphorus content, but deficient in nitrogen. Apparently the mechanism for the conversion of carbohydrate to fat was interfered with in the development of these deficiencies.

The deficient cells assimilate the element they lack either in the light or in the dark (Ketchum, '39). An example of recovery is included in tables 5 and 6. The composition of the cells was nearly normal after one day's growth in the light. In the dark, the recovery was not nearly so complete.

DISCUSSION

These observations show that various species of algae have an inherent tendency to contain similar proportions of essential elements when grown under similar environmental conditions. It is of interest that the proportions of carbon and nitrogen in the cells of the fresh water Chlorophyceae are so similar to their proportion in the marine diatom and in natural populations of marine phytoplankton. This consistency lends credence to the usefulness of conversion factors for estimating the total size of natural populations from the determination of one of its characteristic properties. Unfortunately, the element most easily determined, namely phosphorus, is one of the most variable characteristics of algae cells. Even in cultures of the same species the phosphorus content showed an average standard deviation of 30% and differences between individual cultures and the average were as great as 50%.

In spite of the inherent consistency of composition large variations may be induced by environmental changes. The estimation of the size of the plankton population must, therefore, be applied with caution, especially when the water in which the algae grew is deficient in one of the elements

being determined. The fact that our analyses of cultures agree so well with natural populations suggests that algae ordinarily produced in natural environments are not deficient. Phosphorus again may be an exception since the natural collections appear to contain less of this element than do our cultures.

It is realized, of course, that these experiments were conducted on the most easily cultured species of green algae and on a marine diatom which has been maintained for many years under laboratory conditions. It is quite probable that other species of algae may be characteristically different from those we have studied. It would be very desirable to have many more analyses of natural collections of different species to determine how general the consistency we have observed is among natural populations.

SUMMARY

1. Some physical and chemical properties of five species of Chlorophyceae, (*Stichococcus bacillaris, Chlorella pyrenoidosa, C. vulgaris, Scenedesmus obliquus, S. basilensis*) and the marine diatom *Nitzschia Closterium* have been determined.

2. The average dry weight and volume of the cells in cultures of *Stichococcus bacillaris* and *Chlorella pyrenoidosa* show an almost twofold variation. The younger, rapidly growing populations vary more than do the older ones. The percent solids in the cells varies from about 20–30%.

3. Individual cells may vary widely from the average in size. Cells in dilute, rapidly growing *Chlorella pyrenoidosa* cultures showed a diameter variation corresponding to a thousandfold range in volume. The size distribution becomes more homogeneous as the culture ages.

4. The proportions of carbon, hydrogen and nitrogen in the different species vary no more than do various cultures of a single species. The proportions of these elements in algae grown in pure cultures are very similar to their proportions in natural collections of phytoplankton, and to the ratios inferred from the changes in their concentration in sea water.

5. The phosphorus and ash content show greater variations, but the ratio ash: phosphorus varies little in spite of the threefold variation in the quantities present. The marine diatom, *Nitzschia Closterium* and the more dilute *Stichococcus bacillaris* cultures contain about the same proportions of phosphorus as natural collections. All of the other algae cultured contained greater proportions of phosphorus.

6. The proportions of organic constituents have been calculated from the elementary composition. All species, including the marine diatom, have similar proportions of fat, protein and carbohydrate in the cells.

7. The composition of cells deficient in phosphorus and nitrogen, and the changes in composition as the cells recover from their deficiencies are presented.

LITERATURE CITED

Cooper, L. H. N. 1938 Salt error in determinations of phosphate in sea water. Redefinition of the anomaly of the nitrate-phosphate ratio. Jour. Marine Biol. Assoc. United Kingdom, *23* (1): 171–179.

Fieser, L. F. 1935 Experiments in Organic Chemistry, p. 350. D. C. Heath and Company.

Fleming, R. H. 1940 The composition of plankton and units for reporting populations and production. Sixth Pac. Sci. Cong. Cal. 1939, Proc., *3:* 535–540.

Franzew, A. W. 1932 Ein Versuch der physiologischen Erforschung der Produktionsfähigkeit des Moskauflusswassers. (In Russian, German Summary) Mikrobiologia (U.S.S.R.), *1:* 112–130.

Haskins, H. H. 1941 The chloroplast pigments in *Chlorella pyrenoidosa.* Thesis, Harvard Univ., Dept. of Biol., 115 pp.

Ketchum, B. H. 1939 The development and restoration of deficiencies in the phosphorus and nitrogen composition of unicellular plants. J. Cell. and Comp. Physiol., *13:* 373–381.

Ketchum, B. H., L. Lillick and A. C. Redfield 1949 The growth and optimum yields of unicellular algae in mass culture. J. Cell. and Comp. Physiol., *33* (3): 267.

Pregl, F. 1930 Quantitative Organic Microanalysis. 2nd English Edition, P. Blakiston's Son and Co., Phila., 109.

———— 1935 Die quantitative organische Mikroanalyse 4, Neubearb. und erweiterte Aufl. von Dr. Hubert Roth, J. Springer, Berlin, 47.

Redfield, A. C. 1934 On the proportions of organic derivatives in sea water and their relation to the composition of plankton. James Johnstone Memorial Volume, Univ. of Liverpool, 176–192.

Redfield, A. C., H. P. Smith and B. H. Ketchum 1937 The cycle of organic phosphorus in the Gulf of Maine. Biol. Bull., *73:* 421–443.

RILEY, G. A. 1946 Factors controlling phytoplankton populations on Georges Bank. Sears Found: J. Mar. Res., *6:* 54–73.

———— 1947 Seasonal fluctuations of the phytoplankton populations in New England coastal waters. Sears Found: J. Mar. Res., *6:* 114–125.

RODHE, W. 1948 Environmental requirements of fresh water plankton algae. Symbolae Botanicae Epsalienses *X:* 1, 149.

SCOTT, G. TAYLOR 1943 The mineral composition of *Chlorella pyrenoidosa* grown in culture media containing varying concentrations of calcium, magnesium, potassium, and sodium. J. Cell. and Comp. Physiol., *21* (3): 327–338.

SPOEHR, H. A. AND H. W. MILNER 1949 The chemical composition of *Chlorella;* Effect of environmental conditions. Plant Physiol., *24:* 120–149.

Contribution No. 478

Reprinted from JOURNAL OF METEOROLOGY, Vol. 6, No. 6, December, 1949, pp. 426–427
Printed in U. S. A

EVAPORATION (MEASURED) FROM OCEAN INTO HYDROSTATICALLY STABLE AIR

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Low-level aircraft soundings at successive distances offshore in winds from land have permitted the construction of vertical cross sections showing the air's over-water modification, the study being limited to soundings for which the unmodified air was warmer than the water and was homogeneous in the lowest 1000 ft. In the paper (Craig, 1949) reporting this study the cross sections have been used to determine values of the relative evaporation $E/(q_0 - q_1)$, where E is rate of evaporation per unit horizontal area, q_0 is specific humidity at the air–water interface, and q_1 is specific humidity of the initial, unmodified air. For the same soundings the present note supplies values of the humidity deficit $q_0 - q_1$ and of the resulting unit-area rate of evaporation. Rates of evaporation measured in this way are subject to large random errors of sampling but are novel in being absolute determinations (subject to presumably small errors due to non-parallel air flow). Measured rates of evaporation from the ocean have never previously been published.

The first six columns of table 1 are reproduced from table 1 of the previous paper. Each value of $E/(q_0 - q_1)$

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TABLE 1. Results of aircraft soundings over Massachusetts Bay in July–October 1944. The difference $T_1 - T_0$, where T_1 is the surface temperature of the initial, homogeneous air and T_0 is the interface temperature, is the temperature excess.

Group	Sounding designator	$T_1 - T_0$ F	Wind speed at 1000 ft mi hr^{-1}	Wind force at surface Beaufort	Distance from land miles	$10^3(q_0 - q_1)$	$E/(q_0 - q_1)$ 10^{-3} dg cm^{-2}s^{-1}	E dg cm^{-2}hr^{-1}
I	A156	3.4	28	4	8	2.7	7.65	0.074
	C236	4.9	23	3	10	6.3	7.65	.174
	A142	3.8	25	4	25	3.8	2.06	.028
	B14	4.6	30	5	45	3.9	1.46	.021
II	C199	6.9	15	3	3	1.2	3.02	.013
	C200	6.1	15	3	13	1.0	3.22	.012
	C201	6.6	15	3	25	0.9	2.06	.007
III	C235	7.5	21	3	2½	5.4	4.97	.097
	C140	7.8	21	3	10	3.9	1.65	.023
	A120	7.7	22	—	24	5.2	2.14	.040
	A71	7.0	25	3	28	5.5	2.14	.042
IV	C136	8.2	25	2	2	3.6	3.91	.051
	C119	11.9	20	—	8	3.9	3.37	.047
	C137	9.4	25	3	9	2.9	3.37	.035
	C143	11.6	22	2	14	3.8	3.11	.043
	A69	10.6	24	3	18	3.4	3.11	.038
	A70	9.0	21	3–4	21	5.2	1.74	.033
	C141	8.4	22	3	26	3.8	1.74	.024
V	C150	11.5	15	2	2½	−3.2	2.34	−.027
	C144	10.1	16	1	8	3.4	1.04	.013
	C151	9.4	13	2	10	−2.4	1.04	−.009
	C149	9.7	13	2	24	−2.7	0.44	−.004
	C37	8.4	15	2	30	4.6	0.44	.007
	C152	10.6	15	3	36	−3.4	0.44	−.005
VI	C229	13.0	30	4	2	2.6	6.77	.063
	C118	15.0	40	3	8	0.0	2.94	.000
	C230	10.9	35	4	9	3.1	2.94	.033
	C119	12.0	35	4	12	1.6	2.94	.017
	C231	11.0	35	4	23	2.9	2.98	.031
VII	C104	17.4	18	2	2	−2.3	2.40	−.020
	C227	18.6	18	2	3	3.8	2.40	.033

is the average of the values, from table 2 of the previous paper, for the two spans adjacent to the sounding, except that for each farthest offshore sounding the value for the single adjacent span is copied. It may be noted that the values of $E/(q_0 - q_1)$ were determined from the modifications of both humidity and temperature in composite sections ('groups' in table 1) consisting of soundings from various occasions similar in regard to temperature excess and wind. The values in the last column of table 1 are the product of the values in the preceding two columns.

REFERENCE

R. A. Craig, 1949: Vertical eddy transfer of heat and water vapor in stable air. *J. Meteor.*, 6, 123–133.

Contribution No. 484

THE FORAMINIFERA

FRED B. PHLEGER

INTRODUCTION

THE Foraminifera have been studied from the long core taken at the John Hancock Building site, and also from samples taken stratigraphically above the core. In addition, several samples of clay from Lynn, Saugus, and Cambridge, Massachusetts, have been searched for Foraminifera. The purposes of this study are: (1) to determine the stratigraphic sequence of the Foraminifera above bedrock at the John Hancock Building site, (2) to determine, if possible, the environment represented by the various faunas in the core, and (3) to determine the environment of deposition of the clays in neighboring areas believed to be correlatives of the lower clay in the present core.

The writer is grateful to Mr. Johnson for the privilege of studying this interesting core. Most of the samples were prepared by Miss Rita Johnson at the Cushman Laboratory for Foraminiferal Research, through the courtesy of Dr. Joseph A. Cushman. Frances L. Parker has checked identification of the species, also at the Cushman Laboratory. William R. Walton prepared many of the samples for study. This work was in part financed by the Office of Naval Research, under contract N6-ONR-277.

METHOD OF STUDY

One-quarter section of the core was furnished for study of the Foraminifera content. This was extracted and prepared by Mr. Johnson and his colleagues and was cut into six-inch lengths, with the top and bottom of each section indicated. The top two inches of each six-inch section furnished was washed and examined for Foraminifera. About one-eighth inch of material was trimmed from the outer surfaces to avoid contamination of the microfaunas which may have been caused by smearing on the inside of the Shelby tubing or in quartering the core.

It was discovered that most of the two-inch sections of samples from beneath the Lower Peat layer (below elevation −24 feet 8 inches) contained few or no specimens of Foraminifera. It seemed important to find whether Foraminifera were present in this lower section of the core, as a basis for knowing whether most of it is of marine or non-marine origin. According-

ly, the complete six-inch section was washed and examined for each of the following samples: 4B, 4C, 4D, 4E, 5C, 6A, 6E, 7A, 7B, 7E, 7F, 7G, 8A, 8B, 8F, 8G, 9A, 9B, 9C, 9E, 9F, 9G, 10C, 11A, 11B, 11C, 12B, 13A, 13B, 13D, 13G, 14D, 15B, 15F, 16D, 17A, 17E, 18C, 18D, 18E, 19C, 19G, 20D, 21,D, 22E, 23B, 23D. Although the results of this examination were mostly negative, a few specimens were discovered and it is believed that the additional effort was justified.

All specimens have been mounted on faunal slides and are in the collections of the Marine Foraminifera Laboratory. In listing the occurrence of specimens, the actual number occurring in each sample is given. Samples taken from the lower peat and above it were approximately two inches in length, and the samples below the peat which contain Foraminifera are all six inches long. Each of these two suites of samples thus contain comparable quantities of sedimentary material, and the relative abundance of the faunas is indicated by the numbers of specimens.

SPECIES OF FORAMINIFERA

The stratigraphic distribution of the Foraminifera is given on Tables XIII and XIV. The following species have been discovered in the samples examined:

Ammoastuta salsa Cushman and Broniman. Plate XIV, 11, 30. Cushman and Broniman, 1948, Contr. Cushman Lab. Foraminiferal Res., vol. 24, p. 17, pl. 3, figs. 15, 16. This species has been described from brackish water of Trinidad, B. W. I. It occurs only in sample 3G in the core. This sample is in the upper part of the lower peat, at a position where Conger found brackish water diatoms.

Eggerella advena (Cushman). Plate XIV, 10. *Verneuilina advena* Cushman, 1922, Res. Hudson Bay Exped., 1920, no. 9, p. 9. This species occurs commonly in the shallow waters off the New England coast and in shallow water from the Arctic and the British Isles. It is suspected that it is characteristic of waters having an approximate salinity range of 30 parts per thousand to 32 parts per thousand, and low winter and high summer temperatures.

Elphidium incertum (Williamson) var. *clavatum* Cushman. Plate XIV, 18. Cushman, J. A. 1930, Bull. 104, U.S. Nat. Mus., pt. 7, p. 20, pl. 7, fig. 10. This variety is a typical shallow water form occurring along the New England coast and also from other Atlantic areas. From its distribution it appears to tolerate a wide variety of water conditions, being perhaps most common in shallow water having low winter temperatures. It probably also represents marine water of rather low salinity.

TABLE XIII. FORAMINIFERA FAUNAS FROM SAMPLES ABOVE THE LOWER PEAT

SAMPLE						1A	1B	1C	1D	1E	1F	2A	2B	2C
Elevation of Foraminifera Sample	+1	+0	−1	−2	−3	−12′5″ to −12′7″	−12′11″ to −13′1″	−13′5″ to −13′7″	−13′11″ to −14′1″	−14′5″ to −14′7″	−14′11″ to −15′1″	−16′2″ to −16′4″	−16′8″ to −16′10″	−17′2″ to −17′4″
PLANKTONIC SPECIES														
Globorotalia truncatulinoides	1													
Pulleniatina obliquiloculata														
BENTHONIC SPECIES														
Ammoastuta salsa														
Cibicides sp.														
Eggerella advena	1													
Elphidium incertum var. *clavatum*						36	54	23				3	3	
Haplophragmoides sp.														
Nonion tisburyensis						66	19	88					6	4
Quinqueloculina cf. *fusca*														
Rotalia beccarii var. *sobrina*						10	1	4						
Trochammina inflata	4	11	78	54	28	6	8			3		1		
Trochammina macrescens				3	1									
Trochammina sp.	1		1	1	3									

SAMPLE	2D	2E	2F	2G	3A	3B	3C	3D	3E	3F	3G	4A	4B
Elevation of Foraminifera Sample	−17′8″ to −17′10″	−18′2″ to −18′4″	−18′8″ to −18′10″	−19′2″ to −19′4″	−19′11″ to −20′1″	−20′5″ to −20′7″	−20′11″ to −21′1″	−21′5″ to −21′7″	−21′11″ to −22′1″	−22′5″ to −22′7″	−22′11″ to −23′1″	−23′8″ to −23′10″	−24′4″ to −24′6″
PLANKTONIC SPECIES													
Globorotalia truncatulinoides													
Pulleniatina obliquiloculata													1
BENTHONIC SPECIES													
Ammoastuta salsa				2		1	1		2		3		
Cibicides sp.			1										
Eggerella advena													
Elphidium incertum var. *clavatum*		3					1						
Haplophragmoides sp.										3	15		
Nonion tisburyensis	1					14	2						
Quinqueloculina cf. *fusca*												4	
Rotalia beccarii var. *sobrina*		2		2		1		1		1			
Trochammina inflata		2	2				1					7	
Trochammina macrescens													
Trochammina sp.										10	11	5	

TABLE XIV. FORAMINIFERA OCCURRING BELOW THE LOWER PEAT

Sample No.	Elevation	Species	No.
7 A	−33′11″ to −34′5″	*Globigerinoides sacculifera*	1
		Sphaeroidinella dehiscens	1
7 F	−36′5″ to −36′11″	*Cibicides* sp.	1
		Globorotalia truncatulinoides	1
8 F	−40′2″ to −40′8″	*Cibicides* sp.	1
9 E	−43′5″ to −43′11″	? *Robulus*	1
13 D	−60′2″ to −60′8″	*Cibicides* sp.	1
		Globigerinoides rubra	1
		Pulleniatina obliquiloculata	1
18 E	−79′8″ to −80′4″	*Nonion tisburyensis* Butcher	3
19 G	−84′7″ to −85′1″	*Nonion* sp.	1
23 B	−97′11″ to −98′5″	*Nonion tisburyensis* Butcher	1

Nonion tisburyensis Butcher. Plate XIV, 17, 25, 36. Butcher, W. S., 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 22, text figs. 1, 2. Butcher has described this species from Tisbury Great Pond, Martha's Vineyard, Massachusetts. It is also found in Great Pond at Falmouth, Massachusetts, and presumably it occurs in other similar places along the coast of Massachusetts. Tisbury Great Pond contains brackish water having a salinity which varies from 20 parts per thousand to 30 parts per thousand, and is occasionally frozen in the surface during the winter. *Nonion tisburyensis* is closely related to *N. pauciloculum* and there may be intergrades between the two species. It is possible that *N. tisburyensis* is a brackish water subspecies of *N. pauciloculum*.

Rotalia beccarii (Linnaeus) var. *sobrina* Shupack. Plate XIV, 15, 16. Shupack, B., 1934, Amer. Mus. Novitates, No. 737, p. 6, figs. 4a-c. The material from which Shupack described this variety is from Long Island Sound and New York Harbor. This is a shallow water area having a surface salinity which generally is between 25 parts per thousand and 30 parts per thousand. It is quite probable that this variety also occurs in Boston Bay and adjacent regions but has not been recognized.

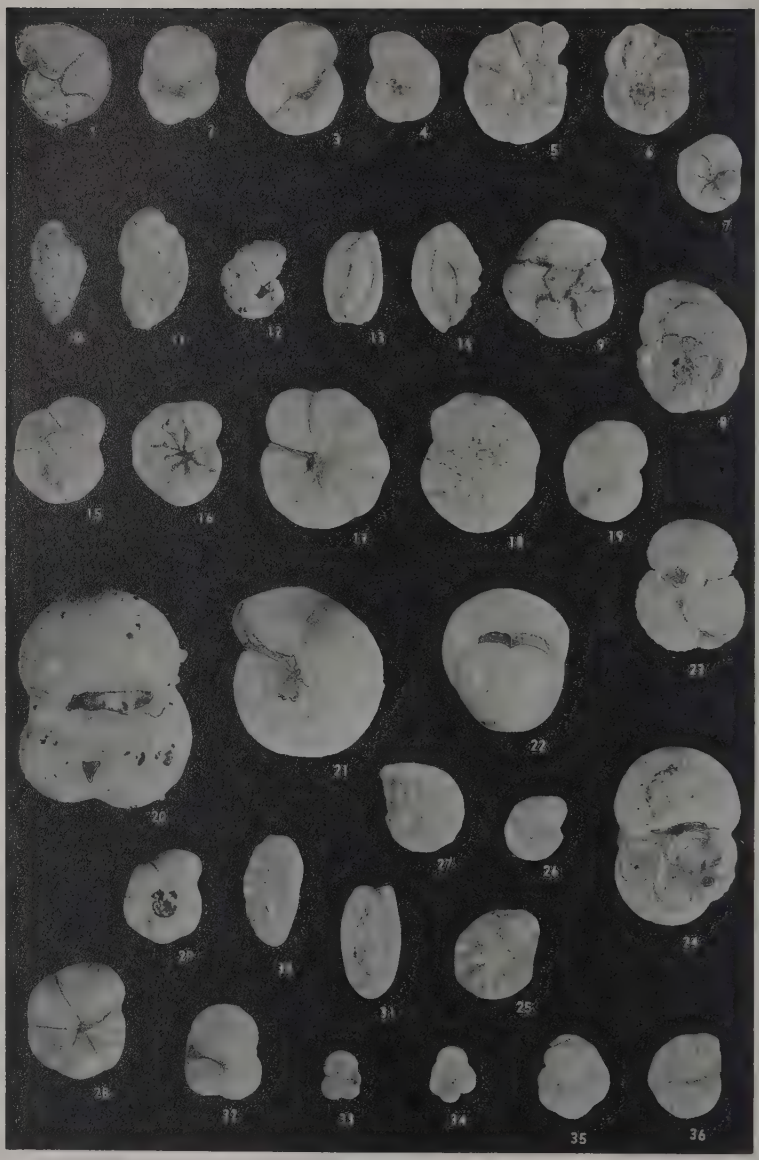

PLATE XIV

(See opposite page for explanation.)

Plate XIV

Foraminifera From Boston Basin Deposits.

1. *Globorotalia truncatulinoides* (d'Orbigny) (x48) Hancock Life Insurance Building site, elevation -1 ft.
2. *Pulleniatina obliquiloculata* (Parker and Jones) (x70) Hancock core, sample 4-B.
3, 4. *Trochammina inflata* (Montagu) (x48) Hancock Life Insurance Building site, elevation -2 ft.
5, 6. *Trochammina macrescens* H. B. Brady (x48) Hancock Life Insurance Building site, elevation -2 ft.
7. *Trochammina* sp. (x48) Hancock core, sample 4-A.
8, 9. *Trochammina* sp. (x48) Charles River silt.
10. *Eggerella advena* (Cushman) (x70) Hancock Life Insurance Building site, elevation -2 ft.
11. *Ammoastuta salsa* Cushman and Bronnimann (x48) Hancock core, sample 3-G.
12. *Haplophragmoides* sp. (x48) Hancock core, sample 3-F.
13, 14. *Quinqueloculina* cf. *fusca* (C. H. Brady) (x70) Hancock core, sample 4-A.
15, 16. *Rotalia beccarii* (Linnaeus) var. *sobrina* Shupack (Fig. 15, x70; Fig. 16, x48) Hancock core, sample 1-C.
17. *Nonion tisburyensis* Butcher (x48) Hancock core, sample 1-C.
18. *Elphidium incertum* (Williamson) var. *clavatum* Cushman (x48) Hancock core, sample 1-C.
19. *Cibicides* sp. (x70) Hancock core, sample 2-F.
20. *Sphaeroidinella dehiscens* (Parker and Jones) (x48) Hancock core, sample 7-F.
21. *Globorotalia truncatulinoides* (d'Orbigny) (x48) Hancock core, sample 7-F.
22. *Puelleniatina obliquiloculata* (Parker and Jones) (x48) Hancock core, sample 13-D.
23. *Globigerinoides rubra* (d'Orbigny) (x48) Hancock core, sample 13-D.
24. *Globigerinoides sacculifera* (H. B. Brady) (x48) Hancock core, sample 7-A.
25. *Nonion tisburyensis* Butcher (?) (x70) Hancock core, sample 18-E.
26. *Nonion* sp. (x70) Hancock core, sample 19-G.
27. *Robulus* (?) (x70) Hancock core, sample 9-E.
28, 29. *Trochammina inflata* (Montagu) (Fig. 28, x70; Fig. 29, x48) Charles River silt.
30. *Ammoastuta salsa* Cushman and Bronnimann (x48) Charles River silt.
31. *Quinqueloculina* cf. *fusca* (H. B. Brady) (x70) Charles River silt.
32. *Globigerinoides rubra* (d'Orbigny) (x70) Charlestown Navy Yard, elevation -56.5 ft.
33. Young Globigerinid (x70) Cambridge clay pit, elevation -50 ft.
34. Young Globigerinid (x70) Charlestown Navy Yard, elevation -41 ft.
35. *Globorotalia* sp. (x70) Charlestown Navy Yard, elevation -56.5 ft.
36. *Nonion tisburyensis* Butcher (x48) Charlestown Navy Yard, elevation -56.5 ft.

Trochammina inflata (Montagu). Plate XIV, 3, 4, 28, 29. *Nautilus inflatus* Montagu, Test. Biut., Suppl., 1808, p. 81, pl. 18, fig. 3. It is possible that this species lives in the adjacent shallow water marine area at the present time although it has not been reported adjacent to Boston. It occurs in abundance in a marine marsh and adjacent nearshore areas off Barnstable, Massachusetts.

Trochammina macrescens H. B. Brady. Plate XIV, 5, 6. H. B. Brady in G. S. Brady, Robertson, and H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 290, pl. 11, fig. 5. This has been reported only from the region of the British Isles, but the species in the present sample may live in the Boston region at the present time. Heron-Allen and Earland suggest that it is a low-salinity form.

The genus *Trochammina* is generally characteristic of marine waters of low salinity to brackish water, and it usually occurs in these environments in some abundance. Various species of the genus also occur in oceanic areas, suggesting that *Trochammina* has a wide range of tolerance for both salinity and temperature variation.

The following planktonic species were found represented, usually by single specimens in one or more samples:

Globorotalia truncatulinoides (d'Orbigny)
Globigerinoides rubra (d'Orbigny)
G. sacculifera (H. B. Brady)
Pulleniatina obliquiloculata (Parker and Jones)
Sphaeroidinella dehiscens (Parker and Jones)

These species are all characteristic of the tropical and sub-tropical waters of the Gulf Stream System. These waters have a surface temperature range of approximately 65° to 80° F. in this latitude and a high salinity (approximately 36.5 parts per thousand). Masses of water escape from the Gulf Stream System and carry this planktonic fauna over the continental slope and shelf where it is deposited in the sediments.

THE FORAMINIFERA FAUNAS

Foraminifera occur in some abundance from sample 4A, at elevation −23 feet 10 inches to the top of the core, at elevation −12 feet 5 inches, and also in the samples which were taken from elevation −3 feet to +1 foot. No Foraminifera were found in the samples furnished from the clay pits at Cambridge, Lynn, and Saugus. Below elevation −24 feet 6 inches Foraminifera are very rare in occurrence, a total of only 14 specimens having

been discovered occurring in only 8 of the 116 samples from this section of the core.

The Upper Silt

From just above the top of the Lower Peat to elevation +1 foot, the faunas are essentially similar. They are dominated by *Elphidium incertum* var. *clavatum*, *Nonion tisburyensis*, *Rotalia beccarii* var. *sobrina*, and at least two different species of *Trochammina*. This fauna is essentially the same as the present-day fauna which lives in shallow marine coastal waters of low salinity from the region from Portsmouth, New Hampshire, to Long Island Sound. It is suggestive of rather brackish water which is found near the mouths of estuaries in the region, having a salinity ranging from approximately 25 parts per thousand to 30 parts per thousand. The faunas show some variation in this section. Samples 3E to 3C, from elevation −22 feet 1 inch to −20 feet 11 inches, contain essentially no Foraminifera. There are also practically no specimens in samples 1F to 1D, from elevation −15 feet 1 inch to −13 feet 11 inches. These two zones may represent times either of very rapid sedimentation when the Foraminifera were diluted by the rapid accumulation of detritus or times when the salinity of the water was especially low and these microfaunas did not thrive in abundance.

There is also a rather striking faunal change between the top core sample (1A) at elevation −12 feet 5 inches, and the samples taken from elevation −3 feet to +1 foot. *Elphidium incertum* var. *clavatum*, *Nonion tisburyensis*, and *Rotalia beccarii* var. *sobrina* are abundant in core samples 1A to 1C but do not occur in the samples taken above elevation −3 feet. These upper samples are characterized by abundant specimens of three species of *Trochammina*. The interpretation of this faunal change is in doubt although it certainly indicates a change in the environment in which the calcareous Foraminifera no longer existed and were replaced by a fauna composed entirely of arenaceous species. It is suggested that this change may be correlated with the change in the type of sediment being furnished, as shown by the change in median diameter of the sediments above elevation −11 feet recorded by Judson. Recent unpublished studies of Foraminifera faunas from the shallow waters of the Gulf of Maine, off Portsmouth, New Hampshire, have shown a very striking adjustment of the calcareous and arenaceous faunas to the material of the marine bottom sediment in and on which they live. In general, the arenaceous faunas appear to be adapted to silt areas in which the sediment has a very small median diameter.

The occurrence of two specimens of planktonic Foraminifera in this upper section of the sediment should be indicated. One specimen of *Globorotalia*

truncatulinoides occurs at elevation +1 foot, the uppermost sample studied from the section, and a specimen of *Pulleniatina obliquiloculata* occurs in sample 4B in the middle part of the Lower Peat. As indicated above, these species are characteristic of Gulf Stream water and do not live in the shallow coastal waters of the area at the present time. Their occurrence within this fauna is thus eccentric, and it is believed that they were introduced in stranded masses of Gulf Stream water as discussed below. The occurrence of *P. obliquiloculata* in sample 4B, within the Lower Peat at elevation −24 feet 4 inches to −24 feet 6 inches, clearly shows that this part of the peat is marine.

The Lower Clay Layers

The faunas which occur in the clay below the Lower Peat may be considered as a unit. One striking feature of this material is the sparsity of Foraminifera; specimens were discovered only in samples 7A, 7F, 8F, 9E, 13D, 18E, 19G, and 23B. Three specimens were found in two samples, two specimens in two samples, and only one specimen occurred in the remaining four samples. Another striking feature of these sparse faunas is the occurrence of the Gulf Stream planktonic species in samples 7A, 7F, and 13D.

The presence of Foraminifera in the Lower Clay layers indicates that it was deposited in marine or brackish water, at least during the time of deposition of the samples containing specimens of Foraminifera. It is suggested that all the clay probably was deposited under essentially similar conditions and, if a sufficiently large area could have been sampled, that occasional Foraminifera may have been found at most of the levels. The sparseness of the fauna clearly indicates that the sediment and the enclosed Foraminifera were deposited under conditions quite different from those now obtaining in this area. This also is indicated by the absence of diatoms, as shown by Conger in the accompanying paper. The presence of *Nonion tisburyensis* suggests brackish water conditions, at least in two samples.

It is suggested that these Lower Clay layers were accumulated under conditions of very rapid sedimentation in an estuary. It appears probable that this was during late Glacial or early post-Glacial time in this area, when there was abundant melt water coming from disintegrating glacial ice in the coastal New England region. Under these conditions, the supply of fresh melt water would be expected to be quite variable, due to variations in weather. The estuarine areas in Boston region would thus be subjected to wide ranges in salinity, ranging from water of almost no salt content to an upper limit of perhaps 20 parts per thousand or 25 parts per thousand with a preponderance of lower salinity.

These two factors, rapid and variable rate of deposition and highly variable

salinity, would discourage large populations of Foraminifera. Rapid and large variations in salinity alone might account for the almost complete absence of diatoms, of either fresh water, brackish water, or marine types. It is believed that there are no plant or animal populations which can withstand large and sudden salinity variations. In addition, rapid accumulation of fine-grained sediment is not conducive to the survival of benthonic Foraminifera. This may be due to the paucity of available oxygen a short distance beneath the surface and also due to the poisonous substances produced by the anaerobic bacteria. Recent unpublished work by the writer has shown that living benthonic Foraminifera appear to be confined to the upper centimeter (or less) of the sediment.

The planktonic Foraminifera found in the clay certainly were not indigenous to the area and must have been introduced from Gulf Stream water. The method by which this occurs has been adequately established by Church[1] and by recent work at the Woods Hole Oceanographic Institution. Masses of water commonly become detached from the Gulf Stream and invade the continental shelf area. These water masses retain their identity for a period of time which largely depends upon the weather conditions. It is known that these detached masses carry zooplankton and phytoplankton which are representative of the Gulf Stream and foreign to the continental shelf, and Gulf Stream planktonic species occasionally are found in Massachusetts Bay. The tropical planktonic Foraminifera eventually are incorporated into the sediments in the foreign environment.

Stetson and Parker,[2] in their study of the sediments and Foraminifera of the sediments obtained from the Boylston Street excavation, found more species of benthonic Foraminifera in their clay samples than occurred in the samples examined by the writer. The sites from which the two suites of samples were obtained are approximately 800 feet apart, and the clays are presumed to be correlative. The difference in faunas may be due to an accident of sampling, in which case the fauna here listed is not characteristic of the clay in the John Hancock excavation. On the other hand, if this were an estuary, as here postulated, tremendous local variations in microfauna may be expected even over short distances, due to great variations in salinity and rate of sedimentation or a combination of the two.

Four samples containing Foraminifera were examined recently which were taken from similar deposits occurring in the Boston area. These samples were furnished by Henry C. Stetson and D. F. Eschman of Harvard University. One sample is silt from the bank of the Charles River at the site of the excavation for a new bridge and came from approximately elevation 0 feet. This is material which is not being deposited at the present

[1] Church, 1936. [2] Stetson and Parker, 1942.

time but was laid down in the Charles River estuary at some time during the recent past. Two samples came from a clay obtained in cores taken from the Charlestown Navy Yard, at elevations −41 feet and −56.5 feet. One sample was obtained from the Cambridge clay pit at an elevation of approximately −50 feet.

The sample of Charles River silt contains a Foraminifera fauna dominated by *Trochammina inflata* and also containing *Ammoastuta salsa*, *Quinqueloculina* cf. *fusca*, and *Trochammina* sp. The Charlestown Navy Yard sample from elevation −56.5 feet contains 1 specimen of each of the following: *Globigerinoides rubra*, *Globorotalia* sp., and *Nonion tisburyensis*. Each of the other two samples contain 1 specimen of a juvenile Globigerinid which cannot be identified with certainty. These specimens are illustrated on Plate XIV.

It appears probable that the fauna of the Charles River silt sample is to be correlated with the Upper Silt in the core described in this report. Foraminifera from the Cambridge clay pit sample and the Charlestown Navy Yard samples represent an environment similar to the Lower Clay of the core and probably are approximate correlatives of that deposit.

SUMMARY OF CONCLUSIONS

1. The Foraminifera occurring in the silt layers which occur above the Lower Peat in the John Hancock excavation were deposited under conditions similar to those which now obtain in the shallow waters of Massachusetts Bay. Vertical variations in abundance or nature of the fauna suggest minor changes in rate of sedimentation and other ecologic conditions.

2. Fourteen specimens of Foraminifera have been found in eight samples from the clay layers below the lower peat, and these samples are distributed through almost the total thickness of the clay. It is suggested that the lower clay was deposited in an estuary, that the rate of sedimentation was rapid, and that the changes of salinity of the water were numerous and large.

3. No Foraminifera were found in the samples of clay from Lynn and Saugus, Massachusetts. This does not necessarily prove that they are nonmarine.

4. It is suggested that silt from the Charles River, at elevation 0 feet, is to be correlated with the Upper Silt at the John Hancock site. It is suggested that clay beneath the Charlestown Navy Yard and the Cambridge clay pit be correlated with a part of the Lower Clay at the John Hancock site.

Contribution No. 484 from the Woods Hole Oceanographic Institution.

Contribution No. 1 from the Marine Foraminifera Laboratory.

Woods Hole, Massachusetts.

Contribution No. 485

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 1457-1462 SEPTEMBER 1949

PLEISTOCENE RESEARCH

A Review by the Members of the Committee on Interrelations of Pleistocene Research, National Research Council

8. SUBMARINE GEOLOGY AND PLEISTOCENE RESEARCH

By Fred B Phleger

The upper layers of marine sediments hold the key to the Pleistocene (including postglacial) history of the ocean basins, and this can be obtained through the collection and study of long submarine cores. Before the sequence of sedimentary events recorded in these cores can be interpreted we must have an accurate knowledge of the relationship between the sediments now being deposited and their various environments. There is relatively little accurate information on the environmental factors of marine sedimentation, although some of the broader aspects are fairly well understood. Any marine deposit is conditioned by all the features of the environment and cannot be considered as separate from the water above and around it. It is necessary, therefore, to understand all the physical, chemical, and biological aspects of an ocean for a proper understanding of a sediment. Our knowledge of marine environments progresses slowly because of the size of the ocean and the difficulty and expense of study.

A marine sediment may be considered to be composed of two types of materials: (1) inorganic particles of sand, silt, clay, or chemical precipitates; and (2) organic remains, composed of skeletons of organisms, organic carbohydrates, and undifferentiated organic debris. The marine environment conditions the grain size, grain-size distribution, certain inorganic chemical features, and the mass physical properties of a sediment. The environment also determines the nature of the recognizable skeletal organic remains in any marine sediment, since plants and animals have more or less specific adaptations to temperature, salinity, nutrient supply, and other factors. Recognizable skeletons in sediments are the most useful tools in deciphering an environment in which a marine sediment was deposited. The organisms most useful in this respect are the Foraminifera because they occur in all marine and brackish-water sediments and also because of their small size and great abundance. Radiolaria, diatoms, ostracods, and other forms might be used, but generally these are more difficult to work with. It is on the basis of environments indicated by the vertical distribution of Foraminifera faunas that the Pleistocene age of parts of some of the submarine cores collected from areas in the Atlantic, Pacific, and Mediterranean has been suggested.

Foraminifera are both planktonic and benthonic. In deep-sea deposits (2000 meters or more) over 99 per cent of the Foraminifera tests belong to planktonic species, and it is in deep-sea cores that vertical faunal differences have been most common. Recent evidence indicates that the planktonic species may live in abundance throughout a great range in depth—2000 meters or more. Thus any fauna of planktonic Foraminifera may have been conditioned by the entire vertical temperature structure of the water.

Modern Foraminifera assemblages, both planktonic and benthonic, differ in different oceanic areas. A study of the distributional features shows a good correlation between faunas and surface and bottom water temperatures. Other factors also are important, principally salinity and the type of sediment, but it is possible to segregate these ecologic factors from the temperature effect. Hutchins (1947) has analyzed the effect of temperature ranges

on *Balanus balanoides* and other marine organisms based on distribution data of the organisms and correlated with physiological studies. There is no reasonable doubt that Foraminifera populations have temperature adaptations comparable to those demonstrated by Hutchins.

In most of the long cores studied from deep water in middle and low latitudes there is a fauna at some distance beneath the sea floor which was deposited during a time of colder-water conditions than those now obtaining. In the tropical areas of the South Atlantic (Schott, 1935) this colder-water fauna is characterized by the absence of one abundant tropical species. In the Gulf of Mexico (Phleger unpublished) and on the continental slope and basin of the western North Atlantic (Phleger, 1939; 1942) in middle latitudes the cold-water fauna is subarctic or cool-temperate. In the Caribbean the "cold-water" fauna is warm-temperate or cool-temperate (Cushman, 1941; Phleger, 1948). In a few cores from the North Atlantic more than one cold-water fauna is separated by one or more warm-water faunas (Cushman and Henbest, 1940; Phleger and Hamilton, 1946). These colder-water faunas are interpreted as Pleistocene in age, certainly last glacial, and possibly as representing substages of the last glacial. Three long cores from the Tyrrhenian Sea (Phleger, 1947), and cores from the Arabian Sea (Stubbings, 1939), show similar faunal variations.

A reconnaissance study by the author has been made of the Foraminifera faunas of a core 15.4 meters from a depth of 2600 fathoms in the Caribbean Sea. At least 11, and probably 12, shifts from tropical to temperate conditions are indicated by the vertical distribution of the faunas. A thick tropical fauna near the mid-section of the core is suggested as possibly representing the Second Interglacial; further, the core may have penetrated most of the Pleistocene. This core suggests the possibility of glacial substages in the third and second, and possibly the first, glacial stages.

The recognition of these probable glacial stages and/or substages in submarine cores is based on the relationships among the faunas which occur in vertical sequence in any core. The top core fauna is taken as the one representing modern conditions obtaining where the core was collected. Faunas beneath the top one are determined as representing the same or different temperature conditions from the present ones at that place. The species of Foraminifera in these lower faunas are all living at the present time; no submarine core fauna examined by the writer and his colleagues has contained any extinct species. The probable relative surface-water temperatures are determined in a general way, by a comparison of the sequence of core faunas with what is now known of the distribution of modern Foraminifera. Planktonic species are used in this analysis almost exclusively. It is not possible, at the present state of our knowledge, to indicate the actual temperatures indicated by these lower core faunas. One possible exception is in studies now in progress on cores from the Gulf of Mexico: The lower core faunas, late glacial in age, probably were adapted to water temperatures similar to those now obtaining above the continental slope north of Cape Hatteras. This surface-water areas has a yearly maximum temperature about 5° F. less and a minimum temperature about 20° F. less than the present temperatures in the Gulf of Mexico.

Continued study of the vertical faunal variations in submarine cores eventually should make it possible to reconstruct the late Pleistocene history of the oceans. It will be necessary to accumulate more useable information on the ecology of Foraminifera, but some progress is being made in this direction. It should be possible, eventually, to reconstruct for the entire ocean the marine temperature conditions which obtained during a part of the Pleistocene. This knowledge should have an important bearing upon our understanding of the sequence of climatic events on adjacent lands. Such information may be of great value in determining the Pleistocene climates in certain areas which were land bridges for the migration of land vertebrates. According to Claude W. Hibbard (personal communication):

> "Very little is known in regard to the land-bridge via Central America. We know that there has been an exchange of vertebrates over this bridge between South America and North America. There has been considerable speculation about the change of temperature and climate in the Central American region to provide corridors which at present do not exist but should have existed in the past to allow the movement of forms."

The collection and study of cores from approproate marine areas adjacent to Central America should aid in solving this problem.

It is of interest to speculate on the probable general distribution of water temperatures in the ocean during a glacial stage of the Pleistocene. Studies indicate that there was general cooling of the water in middle and low latitudes. This is seen in cores collected in the Gulf of Mexico, low latitudes of the South Atlantic, the Arabian Sea, and the Caribbean, and in middle latitudes of the North Atlantic and Mediterranean. The amount of cooling in degrees would be expected to vary from place to place and may reach as much as 10° F. for summer maximum and perhaps more for winter minimum temperatures. It appears doubtful whether truly Arctic and Antarctic waters were appreciably cooled since these regions now have temperatures which are at an approximate minimum to be expected under any conditions.

The broad features of oceanic circulation would probably be similar to the present circulation, with two important exceptions. The clockwise and counter-clockwise circulation which brings tropical water into high latitudes probably was telescoped into lower latitudes. This would be effected by the greatly enlarged masses of Arctic and Antarctic water acting as a density barrier to the distribution of the warm water as far poleward as at the present time. Ice-rafted pebbles have been collected by Henry C. Stetson and the writer in one submarine core from the western North Atlantic as far south as approximately 40° N. Lat. These probably were deposited by icebergs, and it is to be presumed that the cold Arctic water extended somewhat south of this latitude; quite possibly pack ice extended as far south as 40° N. Lat. Under these circumstances the Gulf Stream system of the North Atlantic undoubtedly would be barred from carrying relatively warm surface water near the European continent, and similar conditions are to be expected in other similar current systems. It is doubtful whether the northern edge of the Gulf Stream system reached a latitude much higher than that of Cape Hatteras on the North American continent.

Lowered sea level during a glacial age and the deflection of the current systems by the masses of cold water would present a series of topographic barriers to oceanic circulation. The main features of this circulation can be reconstructed for the last glacial age on the basis of information already available. There is a further possibility, however, which promises more reliable results. Water masses can be identified by their assemblages of planktonic Foraminifera. There should be no great difficulty in tracing the distribution of water masses for the various stages of the Pleistocene when sufficient core material has become available. This will involve careful correlation of the relatively cold-water lower faunas in the cores, but such correlation is somewhat simplified by the preservation of the complete record in the deep sea. The positions at which deep-sea cores are collected should be determined on the basis of these possibilities.

Another important contribution of this research is the possibility it offers of correlating the North American Pleistocene with that of Europe. This can be aided by the use of pollen as a tie-in from land to sea where a submarine Pleistocene Foraminifera fauna occurs near land. In the Gulf of Maine such a fauna is widespread in short cores taken within 15 miles miles of land. This appears to be an ideal location to make a tie-in between North America and the submarine sequence. A similar tie-in should be possible between the marine sequence and the European glacial sequence in places such as the North Sea.

It appears that the only environment in which an undisturbed record of the complete Pleistocene is preserved is in the ocean basins. It may even be desirable to establish a "type section" for the Pleistocene based upon long cores of deep-sea sediments. The best region for such a purpose is perhaps the Mediterranean where it may be possible to correlate the results with the Pleistocene sequence in the Alps and also with the excellent sequence of prehistoric man in that region (Bradley, 1938). A series of long submarine cores recently have been collected from the Mediterranean by members of Oceanografiska Institutet of Göteborg. Study of these cores will be begun during the summer of 1949 by members of the Marine Foraminifera Laboratory.

There is little published information on conditions of sedimentation in offshore marine areas during the Pleistocene. Daly (1936) and

others have suggested that lowered sea level during a glacial age would expose great areas of mud on the lower part of continental shelves. Wave action on these exposed shelves would put great quantities of fine-grained sediments into suspension. Most of these materials would be deposited on the continental slopes, but some might reach the ocean basins. A relatively thick deposit of fine-grained sediments would accumulate, at least on the slope areas, during a glacial age or subage. In addition, because of lowered sea level, the rivers would be expected to carry greater quantities of sediment into the ocean than at present due to an increase of gradient, at least in the lower parts of river courses.

The sediment containing late-glacial Foraminifera faunas is generally thicker than that containing postglacial faunas on the continental slope areas studied. This is not necessarily true in the sediments collected from the ocean basins far from large land masses, as in the Caribbean. In the Gulf of Mexico, a relatively enclosed basin adjacent to large land areas, sedimentation was rapid in places at great depth during the last glacial age (or subage). Cross-bedded sand was deposited in parts of the Sigsbee Deep at this time (Trask, *et al.*, 1947). Evidence of rapid sedimentation during glacial times is seen in the Tyrrhenian Sea and also in a deep basin adjacent to a large land area (Phleger, 1947).

Large amounts of fine-grained sediment in sediment in suspension would make ocean water much more turbid than at present over large areas of the world. This turbidity would limit the depth of light penetration and thus the depth of effective photosynthesis. The production of marine plankton and all other organisms would be reduced under such conconditions. The writer has observed that Foraminifera populations usually are much smaller in late-glacial than in postglacial marine sediments. It is believed that this is due in part to lower organic production. These apparently lower populations undoubtedly are accentuated by a more rapid rate of deposition of inorganic materials.

Submarine coring devices in use until recently could obtain cores rarely more than 10 feet in length, although one has been reported 17 feet long. Kullenberg (1947) has adapted a piston core sampler which obtains undisturbed cores 20 meters in length in certain types of materials. Use of this instrument will greatly add to our knowledge of oceanic history. The Swedish Deep Sea Expedition recently completed a round-the-world cruise principally to take cores with the Kullenberg sampler. This expedition obtained approximately 200 long cores from all the major ocean basins in low latitudes. This material and the cores being collected by other organizations in this country should provide invaluable data.

The study of the Pleistocene history of the ocean is an infant science, and the present accomplishments are not great. Collection of material from the ocean is expensive, and the subsequent study and interpretation are laborious and specialized. The principal techniques of field work and laboratory study are now established. It is believed that considerable progress will be made in the next few years in determining the sequence of marine events and environments during glacial and interglacial times. This information will aid in analyzing the Pleistocene history of the continents and in understanding the sequence and distribution of environments for the Earth as a whole.

References Cited

Bradley, W. H. (1938) *Mediterranean sediments and Pleistocene sea levels*, Science, vol. 88, p. 376–379.

—— and Henbest, L. G. (1940) *Geology and biology of North Atlantic deepsea cores*, U. S. Geol. Survey, Prof. Paper 196A, pt. 2, p. 35–47.

Cushman, J. A. (1941) *A study of the Foraminifera contained in cores from the Bartlett Deep*, Am. Jour. Sci., vol. 239, p. 128–147.

Daly, R. A. (1936) *Origin of submarine "canyons"*, Am. Jour. Sci., vol. 31, no. 186, p. 401–420.

Hutchins, L. W. (1947) *The bases for temperature zonation in geographical distribution*, Ecol. Mon., vol. 17, p. 325–335.

Kullenberg, B. (1947) *The piston core sampler*, Svenska Hydr.-Biol. Komm. Skr., Tr. Ser.: Hydr., Bd. 1, H.2, p. 1–40.

Phleger, F. B, Jr. (1939) *Foraminifera of submarine cores from the continental slope*, Geol. Soc. Am., Bull., vol. 50, p. 1395–1422.

—— (1942) *Foraminifera of submarine cores from the continental slope, Part 2*, Geol. Soc. Am. Bull., vol. 53, p. 1073–1098.

—— (1947) *Foraminifera of three submarine cores from the Tyrrhenian Sea*, Kungl. Vetensk. Vitterhets Samhälles Hand., Sjätte Fölfden, Ser. B, Bd. 5, no. 5.

—— and Hamilton, W. A. (1946) *Foraminifera of two*

submarine cores from the North Atlantic basin, Geol. Soc. Am., Bull., vol. 57, p. 951–966.

Schott, W. (1935) *Die Foraminiferen in den äquatorialen Teil die atlantischen Ozeans*, Deutsche C. Sudpolar-Exped., II Heft 6, p. 411–616.

Stubbings, H. G. (1939) *Stratification of biological remains in marine deposits*, The John Murray Exped., Sci. Repts., vol. 3, no. 3, p. 159–192.

Trask, P. D., Phleger, F. B, and Stetson, H. C. (1947) *Recent changes in sedimentation in the Gulf of Mexico*, Science, vol. 106, p. 460–461.

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Contribution No. 2, Marine Foraminifera Laboratory

Contribution No. 485, The Woods Hole Oceanographic Institution

Contribution No. 486

Reprinted from the Proceedings of the National Academy of Sciences,
Vol. 35, No., 9 pp. 518–528. September, 1949

*THE PRINCIPLES OF TIME SERIES ANALYSES APPLIED TO OCEAN WAVE DATA**

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Communicated by J. A. Fleming and read before the Academy, April 25, 1949

Introduction.—In the original report on the auto correlation analysis of ocean wave data the apparent advantages of that method over periodogram and Fourier series applications to finite amounts of data were brought out.[1] Because of practical restrictions in that only finite amounts of observational data are available for study, the fitting of wave heights as functions of time by means of trigonometric components is only in special circumstances suitable for describing the physical characteristics of the data itself. In the case of ocean wave data, *a priori* knowledge of frequency is not available, and results from this type of analysis have resulted in claims that sea surface roughness patterns are composed of large numbers of frequencies which have traveled with independent velocities from their regions of generation. In other words, mathematical representations of the data have been assumed to be physically significant, a situation which may lead to apparent misconceptions of the behavior of the phenomenon and of the dynamics causing it. In fact, the fitting of data by any of the various methods of cycle analyses, in the absence of *a priori* knowledge of the physical properties, is no more effective than the fitting of that same data, say, by orthogonal polynomials.[2]

It appears that the problem of understanding the behavior of a physical phenomenon which varies with time is directly associated with that of pre-

dicting its future course from its past behavior, and the distance into the future which the phenomenon may be accurately forecasted may be taken as an indication of the amount of dynamics associated with the phenomenon itself. Thus, in the case of sea surface wave data, while a mathematical theory may be set up from the results of a periodogram or Fourier series analysis to explain a record, it has little physical meaning unless it can be extrapolated into the future. It was from this point of view that Wiener[3] investigated the problem of prediction and defined the dynamics of a time series in terms of the possibility of prediction into the future. The auto correlation of a time series provides a means of doing this. It can be shown that the auto correlation function may be obtained from the spectrum of the series, and the spectrum may also be obtained from the auto correlation function. In this process the spectrum and the auto correlation function of a discrete sequence of observations preserve information by retaining the frequency and the amplitudes of all frequencies from zero to infinity, whereas, on the other hand, it discards information relative to phase relationships.

TABLE 1

RECORD NO.	LOCATION	DEPTH, FT.	DATE	STARTING TIME	RECORD LENGTH, SECS.
B-713a	Bermuda	120	2/21/47	1840	350
B-12a	Bermuda	120	10/25/46	1405	350
1–5B	Cuttyhunk	75	6/14/46	1149	60
39-L	Cuttyhunk	75	7/ 4/46	0627	350
53-W	Cuttyhunk	75	9/15/46	0050	350
53-X	Cuttyhunk	75	9/15/46	0650	350
53-Y	Cuttyhunk	75	9/15/46	1250	350
56-E	Cuttyhunk	75	10/ 1/46	1244	350

The method of auto correlation analysis is employed in the analysis of many types of scientific problems. In addition to its use as a prediction mechanism, the correlograms and the Fourier transforms of the correlograms into power spectra serve to describe the basic data by measuring its physical properties of period, amplitude and damping coefficients which, in turn, may be employed in an attempt to discover something of the physical causes. The results throw new light on the physical properties of the sea surface and on the behavior of ocean wave patterns. The method provides a means for distinguishing between mathematical and realistic physical representations of sea surface roughness patterns.

Computation of the Auto Correlation Coefficient.—Theoretical formulae defining the auto correlation coefficient as developed by Wiener,[3] Khinchine[4] and others are not strictly applicable to practical computations.[5] This is because wave heights are not observed as infinite functions of time (very frequently only short series of observations are obtainable), and also be-

cause the means of such finite series frequently depart from zero. In our computations it was found necessary to use a running mean rather than extracting a grand mean at the very beginning of the computation. To compute the auto correlation coefficient we compute the following statistics from N equally spaced observations for k equally spaced time lags.

$$T_0 = \sum_{i=1}^{N} x_i \qquad T_k = \sum_{i=1}^{N-k} x_i \qquad T_k' = \sum_{i=1}^{N-k} x_{i+k}$$

$$S_0 = \sum_{i=1}^{N} x_i^2, \qquad S_k = \sum_{i=1}^{N-k} x_i x_{i+k}$$

$$S_0 = \frac{NS_0 - T_0^2}{N^2}, \qquad S_k = \frac{(N-k)S_k - T_k T_k'}{(N-k)^2}$$

$$r_k = S_k/S_0$$

The correlogram is obtained by plotting the auto correlation coefficient (r_k) as ordinate against k as abscissa. In this particular investigation the correlogram provides the basis for analysis of the data, and may be transformed into a power spectrum by a Fourier transform of the auto correlation coefficients. This spectrum is identical with that which would be obtained by periodogram analysis of an infinite series.

In the applications considered in this paper the auto correlation function frequently occurs as a composite of a pure sinusoidal wave and one producing a continuous spectrum. The period of the former is given by the correlogram and its amplitude computed from the original data by least squares. The residue after subtraction from the original data consists of a continuous spectrum. This provides a practical example of theorem 3 of Khinchine's theory of correlation[4] in which the auto correlation function is split into a line and a continuous spectrum.

The Data.—This paper presents results of auto correlation analysis of eight ocean wave records. The records are from underwater pressure recorders located at Cuttyhunk, Massachusetts (depth 75 feet), and at Bermuda (depth 120 feet) and represent pressure pulses at the sea bottom transmitted from the sea surface.[6] For the analyses, the records were scaled for pressure values at intervals of one second and were not reduced to sea surface wave heights.[7]

Bermuda Record B-713a is discussed separately. Table 1 summarizes the records analyzed.

The Analysis of Wave Record B-713a.—This record is discussed in more detail than the others for comparison of the results from cycle analyses with those of auto correlation analyses on finite amounts of data. Cycle analysis refers both to mechanical periodogram analysis and to the fitting of data by sums of sines and cosines. Results obtained by the former method, to which the data had already been subjected,[8] are first discussed in the

light of their usual interpretation. This is then supplemented by computation of certain statistical properties of the data and then followed by fitting a series of cosine waves to the data over the critical part of the spectrum. Results obtained by the above methods are then compared with those obtained by the method of auto correlation analysis.

a. Mechanical Periodogram Analysis: The mechanical periodogram analysis of this 20-minute wave record (Fig. 1) shows a continuous spectral distribution with about 32 defined peaks between 8.8 and 40 seconds. The greatest development occurs in the 8- to 10-second band, and maximum energy is indicated for 8.8, 9.0 and 9.5 seconds. The customary interpretation given this type of analysis is that the basic wave pattern is made up of

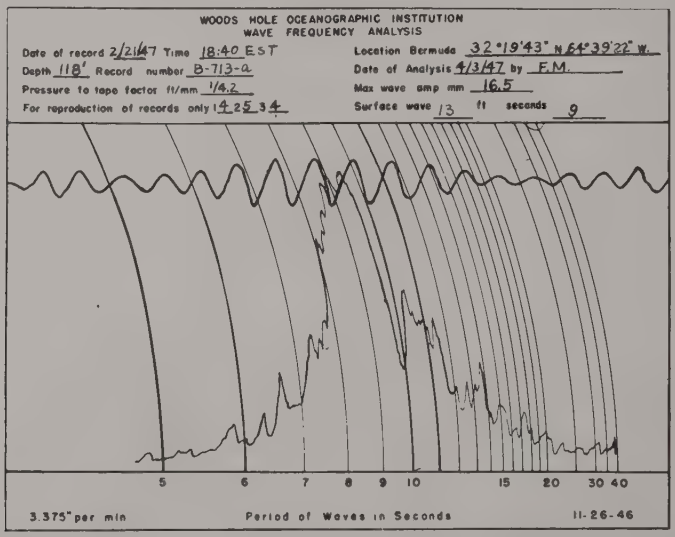
WOODS HOLE OCEANOGRAPHIC INSTITUTION
WAVE FREQUENCY ANALYSIS
Date of record 2/21/47 Time 18:40 EST
Location Bermuda 32°19'43" N 64°39'22" W.
Depth 118' Record number B-713-a
Date of Analysis 4/3/47 by F.M.
Pressure to tape factor ft/mm 1/4.2
Max wave amp mm 16.5
For reproduction of records only 1 2 5 3 4
Surface wave 13 ft seconds 9
5 6 7 8 9 10 15 20 30 40
3.375" per min
Period of Waves in Seconds
11-26-46

FIGURE 1

Results of mechanical periodogram analysis of Wave Record B-713a. See text.

the frequencies indicated. The principal wave periods lie between 6 and 15 or 20 seconds, with the maximum period band of the "wave train" extending from 8 to 10 seconds. The characteristics of different wave records are usually compared by the widths and locations of the maximum band development, together with locations of the individual maximum points. Special consideration is frequently given to indications of longer periods, say above 20 seconds, which are sometimes presumed to be waves generated by oceanic storms at great distances but which have "out-run" the storm itself.

The above physical interpretation is doubtful in that periodogram analyses of finite amounts of data are not necessarily physical, but may be only mathematical representations of the data. Its acceptance as a physical representation without *a priori* reason may lead to a misconception of both the physical properties and the causative mechanism of the sea surface roughness. This question is discussed later after additional results are developed.

b. Statistical Characteristics: The frequency distribution of periods, compiled from measurements of the times between successive wave crests on the record, has the following properties:

Standard deviation = 1.135 seconds
Mean = 8.59 ± 0.077 second
Mode = 8.75 seconds

Thus, the mean and modal values of distances between wave crests in the original record lie in the range of maximum energy brought out by the mechanical periodogram analysis (Fig. 1).

TABLE 2

PERIOD	RELATIVE AMPLITUDE	PHASE ANGLE, °
7.50	1.00	156.6
8.00	2.31	111.9
8.25	2.97	23.6
8.50	4.01	30.1
8.75	4.60	18.9
9.00	5.29	69.6
9.25	10.93	276.9
9.50	3.49	231.2
9.75	2.20	210.2
10.00	0.77	16.9

Amplitude and phase values obtained by fitting cosine waves to Wave Record B-713a.

c. Cosine Wave Analysis: Results obtained by independent least square fits of ten cosine waves (periods from 7.5 to 10.0 seconds) to the basic data are tabulated in Table 2. The spectrum is similar to that obtained by mechanical periodogram analysis, increasing from a minimum at 7.5 seconds to a maximum value at 9.25 seconds and then diminishing rapidly to a minimum at 10.0 seconds. This representation, obtained from a finite amount of data, is like that of the mechanical periodogram analysis—of mathematical significance only and without physical reality. The rôle of this type of analysis is a secondary one, to be applied after the period, or periods, have been established by other means.

d. Auto Correlation Analysis: The correlogram of the primary data of Wave Record B-713a (Fig. 2) maintains a period of 8.75 seconds and damps

FIGURE 2

Correlograms of Wave Record B-713a. Curves have been drawn through values of r computed for each second. The curves have not been smoothed.

slowly; at the end of the third cycle the amplitude is reduced to a value of $r = 0.87$, after which it continues to damp slowly until reaching a terminal value (r_T). The terminal amplitude is maintained by a cyclical component which proceeds undamped through the basic data. It is the fundamental wave to which energy is supplied by an external force at a rate equal to that at which it is dissipated in the system. Its amplitude, obtained from a least square fit of an 8.75-second sine wave to the primary data, is 0.720 foot.

Subtracting the cyclical component ($T = 8.75$ seconds, $A = 0.720$ foot) from the original data, the variance reduces from a value of 0.492 square foot to 0.216 square foot for the residuals. Recomputing the auto correlations of the residuals, the correlogram then damps in a fashion characteristic of an autoregressive series; at the end of the second cycle, the correlogram amplitude is $r = 0.54$ as compared to $r = 0.95$ for that of the primary data (Fig. 2).

The value of the terminal amplitude of the original correlogram is

$$r_T = \frac{\text{Variance cosine}}{\text{Total variance}} = \frac{A^2/2}{\sigma_y^2} = 0.56$$

for Wave Record B-713a. This value also represents the per cent reduction due to the cyclical component itself, and may be expressed as the ratio of the residual (σ_r^2) and original (σ_y^2) variances. Thus:

$$r_T = 1 - \frac{\sigma_r^2}{\sigma_y^2}$$

The numerical solutions of the above and other relations, for cases where the original series consists of a sine term and a random residual, provides a means of checking the computations.

The significant difference between the results of periodogram analyses and correlogram analyses of finite amounts of data is that the former are not the power spectra of the latter. The large number of peaks in the periodogram of Record B-713a (Fig. 1) are not real periods, and they provide only a mathematical representation of the data. The spectrum is similar to that obtained by the arbitrary fitting of cosine waves to the data, and is not to be interpreted as having physical reality.

On the other hand, the use of auto correlation analysis reveals that for Record B-713a the auto correlation function is broken into two parts—one having a line, and the other a continuous spectrum. The line spectrum is that of the cyclical component present in the basic data, whereas the continuous spectrum represents a wide band of frequencies, with an average frequency equal to that of the cyclical components, but which damp out rather rapidly.

The physical interpretation to be given results from the two types of

analyses is equally significantly different. The auto correlation analysis suggests that the physical characteristics of the sea surface wave pattern comprise one fundamental wave with a period of 8.75 seconds and an amplitude of 0.72 foot, on which is superimposed a series of local impulses. The former, generated presumably by a meteorological situation acting at some distance from the target, is the predictable component in the data. It accounts for an estimated 56% of the total variability of the sea surface pattern (obtained from the value of the terminal amplitude of the correlogram) and lends itself to being forecast from knowledge of wind action on the sea surface. The remainder of the data represents a superimposed

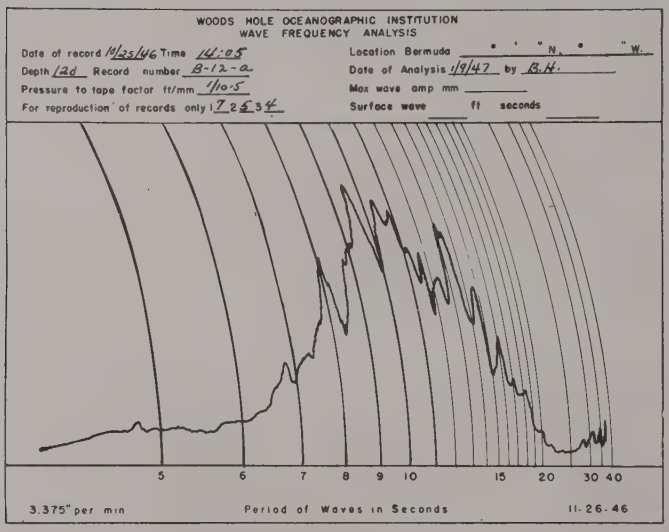
WOODS HOLE OCEANOGRAPHIC INSTITUTION
WAVE FREQUENCY ANALYSIS
Date of record 11/25/46 Time 14:05
Location Bermuda
Depth 12d Record number B-12-a
Date of Analysis 1/9/47 by B.H.
Pressure to tape factor ft/mm 1/10.5
Max wave amp mm
For reproduction of records only 1 2 3 4
Surface wave ft seconds
5 6 7 8 9 10 15 20 30 40
3.375" per min
Period of Waves in Seconds
11-26-46

FIGURE 3

Results of mechanical periodogram analysis of Wave Record B-12a. See text.

series of local impulses which die out rather rapidly. They would appear to be generated by local winds in the area of the target, and their relative significance to the pattern is also evaluated from the terminal amplitude of the original correlogram.

Auto Correlation Analyses of Additional Ocean Wave Records.—The results of auto correlation analyses of seven additional ocean wave records from Cuttyhunk and Bermuda are tabulated in Table 3. The mechanical periodogram analyses of these records gave results similar to those for Record B-713a, each showing approximately 30 peaks. Figures 1 and 3 are representative of this analysis.

The original correlograms do not damp completely (Figs. 2 and 4),[9] terminal amplitudes range from 0.08 to 0.66 and all show well-defined periods ranging from 6.50 to 15.5 seconds. Amplitudes of the cyclical components associated with the data range from 0.10 to 0.72 foot, and their relative quantitative significance to the total sea surface roughness patterns are revealed by the terminal amplitudes (r_T). Five of the records show r_T values

TABLE 3

RECORD NUMBER	ORIGINAL DATA					RESIDUAL DATA		
	σ_y^2	$\frac{AD}{\sigma}$	T	A	rT	σ_r^2	$\frac{AD}{\sigma}$	A'
B-713a	0.492	0.78	8.75	0.72	0.56	0.216	0.78	0.74
B-12a	0.018	0.80	9.07	0.10	0.22	0.014	0.83	0.09
53-W	0.109	0.80	15.50	0.35	0.57	0.047	0.79	0.35
53-X	0.185	0.84	12.25	0.51	0.66	0.064	0.77	0.49
53-Y	0.070	0.82	11.00	0.10	0.08	0.065	0.80	0.10
56-E	0.128	0.80	6.50	0.38	0.56	0.057	0.80	0.38
39-L	0.049	0.82	8.29	0.15	0.25	0.035	0.80	0.15
I-5B	0.030	0.84	8.00	0.19	0.63	0.011	0.83	0.19

Results of auto correlation analyses of ocean wave records. σ_y^2 = variance original data, AD/σ = ratio of average deviation to standard deviation, T = period of correlogram, A = amplitude of cyclical component by harmonic analysis, σ_r^2 = variance residual data, r_T = terminal amplitude of original correlogram, $A' = \sqrt{2(\sigma_y^2 - \sigma_r^2)}$.

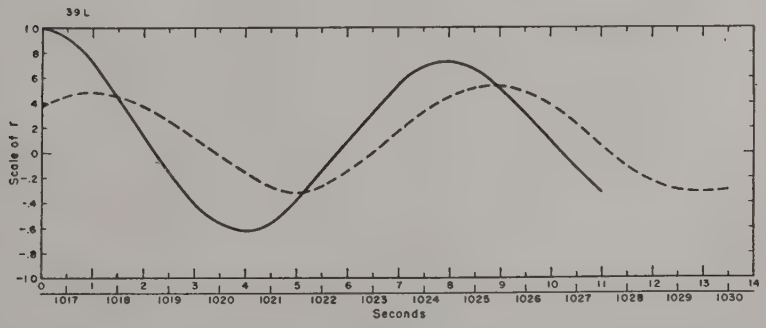

FIGURE 4

Correlogram of Wave Record 39-L, 0 to 11 seconds (solid line) and 1017 to 1030 seconds (dashed line). Curves have been drawn through values of r computed for each second. The curves have not been smoothed.

exceeding 0.5, indicating more than 50% of the roughness pattern resulting from the cyclical component. For the remainder, local influences dominate the pattern, and in one of these, 53-Y, the terminal amplitude of the correlogram is so low (0.08) as to indicate the data to be almost autoregressive. In the complete absence of sea swell the original correlogram damps rapidly to zero.[10]

The results are typical of those obtained from the analyses of more than 30 wave records from the North Atlantic, Mediterranean and the eastern American coast. After extraction of the cyclical components, the residual variances are diminished, and the correlograms of the residuals damp more rapidly in the fashion of an autoregressive series (Fig. 2).

A numerical result of apparent significance is that the ratios of the mean deviations to the standard deviations (for both original and residual data) is approximately equal to $\sqrt{2/\pi}$, a relationship which usually characterizes unimodal curves approaching symmetry. This relationship enables an approximate estimate of the mean sea surface roughness (expressed as twice the average deviation of the original data) to be made directly from the variance of the original data.

The properties of the sea surface roughness pattern, as brought out by auto correlation analysis of a finite amount of data, describe its physical characteristics. They indicate that the instantaneous sea surface pattern is not an interference pattern composed of many wave frequencies which have traveled with independent velocities from their generation areas, such as may be concluded from results of a cycle analysis of finite amounts of data, but rather that it seems to consist of a single cyclical component (sea swell) on which is superimposed random frequencies (local sea) of the same average frequency. The sea swell appears to have been generated by a dominating meteorological situation at some distance from the target and is maintained by energy supplied at a rate equal to that dissipated by the system. It is to be expected that this period changes with time and at a rate dependent on the stability of the off-shore meteorological situation causing it. On the other hand, the local sea is induced by local winds and other factors tending to disturb the sea surface and dies out fairly rapidly.

It may thus be reasoned that the ocean itself acts as a filter which, under specific conditions, passes only certain fundamental frequencies, which we call sea swell. This fundamental frequency at any time is perhaps a function of the characteristics of the ocean basin over which it has traveled, plus wind velocity, direction, fetch and other properties of an established wind-generating system. Its constancy is related to the stability of the meteorological situation. At any particular time local conditions may also produce a continuous band of frequencies with an average frequency the same as that of the sea swell. These latter die out rapidly in a manner similar to the effect of random impulses on a sluggish oscillator as the ocean basin continues to act as a filter.

However, regardless of the exact nature of the physical explanation of the mechanism maintaining the state of the sea, a quantitative separation into sea swell and local sea is fundamental to an understanding of its physical properties. This has an added practical significance for operational purposes as well as for aerial depth determination and for controlled experi-

ments involving sea surface properties. To this end, the method of auto correlation analysis is an improvement over other procedures for the analysis of finite amounts of data in which not even the length of the periods or the recurrence intervals are known or suspected at the outset. The results in themselves provide a more realistic geophysical explanation of the phenomena and avoid the pitfalls from claims of large number of periods and cycles which may arise from procedures less adapted to the available data.

* Contribution No. 486 from the Woods Hole Oceanographic Institution and the Office of Naval Research, Contract N6onr 277/1.

† The methods and conclusions in this paper have partly resulted from a collaboration with Dr. George P. Wadsworth, of the Massachusetts Institute of Technology, who is preparing a theoretical account of the adaptations of generalized harmonic analysis to the specific problems of ocean waves.

[1] Seiwell, H. R., and Wadsworth, George P., "A New Development in Ocean Wave Research," *Science*, **109**, 271–274 (1949).

[2] See also: Bartels, J., "Some Aspects of Geophysical Cycles," *J. Wash. Acad. Sci.*, **26**, No. 5 (1936); Wilson, Edwin B., "The Periodogram of American Business Activity," *Quart. J. Economics*, 375–417 (May, 1934).

[3] Wiener, N., "Generalized Harmonic Analysis," *Acta Math.*, **55**, 117 (1930). "The Extrapolation, Interpolation and Smoothing of Stationary Time Series," NDRC Report, 1942. Prepublication announcements of the later report have been made by John Wiley and Sons, Inc., New York.

[4] Khinchine, A., "Korrelationstheorie der Stationaren Stochastischen Prozesse," *Math. Ann.*, **109**, 604–615 (1934). Translation by T. C. Duke, Dept. of Math., Mass. Inst. Tech., 1949.

[5] See also: Kendall, Maurice G., "The Advanced Theory of Statistics," London, 1948; Bartlet, M. S., *et al.*, "Symposium on Auto Correlation in Time Series," *Supp. J. Royal Statistical Soc.*, **VIII**, No. 1, 27–97 (1946).

[6] Seiwell, H. R., "Results of Research on Surface Waves of the Western North Atlantic," papers in *Phys. Ocean. Meteor.*, **X**, No. 4, 1–56 (1948).

[7] The ratio of amplitudes of instantaneous pressure fluctuations at the sea bottom ΔP_h to those at the sea surface ΔP_s is

$$\frac{\Delta P_h}{\Delta P_s} = 1.35 \frac{1}{\text{Cosh } kh}$$

where h is depth to bottom and $k = 2\pi/\text{wave-length}$. The factor 1.35 has been experimentally determined for the Woods Hole–Bermuda area.

[8] These analyses were performed on the ocean wave analyzer at this Institution. The term mechanical periodogram analysis is used to distinguish it from other types of periodogram analyses. See reference 6.

[9] Correlograms for Record 53-X have been published in reference 1.

[10] Examples of this situation have been encountered, although they are not discussed in this paper.

Contribution No. 496

HORIZONTAL DIFFUSION DUE TO OCEANIC TURBULENCE[1]

By

HENRY STOMMEL

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ABSTRACT

The purpose of this paper is to discuss some fundamental aspects of horizontal diffusion in the sea and to present some observations that were made especially to obtain quantitive data.

The subject falls naturally into two parts:

Part I. It is shown that the classical Fickian equation of diffusion does not describe diffusion in the sea. The Richardson law of diffusion is introduced, and it is shown from observations of diffusion in the ocean that this new equation of diffusion does indeed describe the process.

Part II. Recent theories of turbulence are reviewed. The Weisaecker-Heisenberg theory of the spectrum of turbulence for large Reynolds number and the Kolmogoroff theory of locally isotropic turbulence are discussed. The applicability of these theories to oceanic turbulence is considered. It is shown that a 4/3 law for eddy viscosity is deducible from the theories of Weisaecker-Heisenberg and Kolmogoroff.

Part I seems safely applicable to the ocean because of the inductive nature of the theory. Part II, being deductive, contains certain assumptions and hypotheses which are discussed in some detail. Just how closely the Weisaecker-Heisenberg theory or the Kolmogoroff theory describes the turbulent regime in the ocean is open to question, but the fact that they both predict a 4/3 law, which is observed in certain ranges of scale, demands that they be seriously entertained.

[1] This work was supported from public funds made available through the Office of Naval Research.

[2] Contribution No. 496 from the Woods Hole Oceanographic Institution.

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I. INDUCTIVE METHOD

1. *Introduction.* The word "turbulence" is used in so many loose connections in oceanography that its meaning is often fuzzy and ill-defined. The dictionary definition of turbulence as "tempestuous state" or "great agitation" is obviously of little physical significance, because a physical quantity must be capable of measurement; that is, it must possess a numerical magnitude and dimensions. A fluid flow is said to be turbulent if it possesses a "turbulent velocity," the meaning of which arises in the following manner.

In laboratory experiments it is fairly easy to define the turbulent velocity exactly. For example, when air is drawn through a wind tunnel which is fitted with a coarse mesh screen at the entrance, the flow of air through the tunnel is complicated by large numbers of eddies set up by the screen. The size of these eddies immediately behind the screen is roughly the size of the mesh of the screen. In thinking of the velocity of the air at some fixed point within the wind tunnel it is a natural concept to regard this velocity as the sum of two terms: (1) a *basic velocity* which remains unchanged with time, or, in other words, the time mean velocity; (2) a fluctuating term which depends upon the eddies in the main stream and whose time mean vanishes, this term being called the *turbulent velocity.* Depending on the magnitude of the turbulent velocity, the flow can be said to be more or less turbulent, so that in this sense, and in this sense only, does the word turbulence make physical sense. In mathematical terms we may restate the foregoing remark as follows.

2. *Definition of Turbulent Velocity.* Suppose that at some fixed point the x-component of the fluid velocity is $u(t)$, a function of the time t. If the time mean of $u(t)$ is taken over a sufficiently long time T we approach a mean value U in the following manner,

$$U = \lim_{T \to \infty} \frac{1}{T} \int_0^T u(t)dt \,, \tag{1}$$

where U is called the *basic velocity.* The instantaneous velocity $u(t)$ is therefore expressible in the form

$$u(t) = U + \mathbf{u}(t) \,, \tag{2}$$

where, by definition of U,

$$\lim_{T \to \infty} \frac{1}{T} \int_0^T \mathbf{u}(t)dt = 0 \,. \tag{3}$$

The additional term $\mathbf{u}(t)$ is called the x-component of the *turbulent velocity.* Similarly, the other components of instantaneous velocity

$v(t)$ and $w(t)$ may be expressed as the sums of component basic velocities V and W and component turbulent velocities $\mathbf{v}$ and $\mathbf{w}$.

The time mean square of the turbulent velocity,

$$\overline{\mathbf{u}^2} = \lim_{T\to\infty} \frac{1}{T}\int_0^T \mathbf{u}^2(t)dt\,, \tag{4}$$

does not vanish. The root time mean squares of the turbulent velocity components $\sqrt{\overline{\mathbf{u}^2}}$, $\sqrt{\overline{\mathbf{v}^2}}$, $\sqrt{\overline{\mathbf{w}^2}}$ are often called the component *intensities of turbulence.*

The *kinetic energy* of turbulence is defined as

$$\tfrac{1}{2}\rho\,(\overline{\mathbf{u}^2} + \overline{\mathbf{v}^2} + \overline{\mathbf{w}^2})\,.$$

These definitions show what is meant by turbulent velocity, intensity of turbulence, and energy of turbulence. It is also evident that these definitions depend entirely upon the premise that limits do exist as the value of T becomes very large. In the case of the wind tunnel experiment there is no question that the limits exist.

In large natural bodies of fluid, such as the ocean, it is by no means so obvious that limits do exist. If T is of the order of magnitude of one hour, then small scale turbulence, such as local mixing, will appear in the term $\mathbf{u}(t)$, whereas tidal currents and seasonal changes will occur in the basic velocity U. If a week is taken as T, then tidal currents will fall into the term $\mathbf{u}(t)$. If ten years is taken as T, then the seasonal changes will occur also in $\mathbf{u}(t)$. If a geological age is taken for T, even long range secular changes will appear in the turbulent velocity term $\mathbf{u}(t)$. Thus it is immediately obvious that in a large natural body of fluid the motion is vastly more complicated than in a well controlled wind tunnel. There are eddies of all sizes and velocities present, and it is by no means evident just what the basic velocity and what turbulent velocity should be called. This situation is remediable, however, as may be seen in the Weisaecker-Heisenberg theory. In the foregoing the averages have been time averages exclusively. It is equally possible to use space averages; in fact, we shall do so in the development of the Weisaecker-Heisenberg theory.

3. *The Fickian Equation of Diffusion.* In the Fickian equation of diffusion we assume that the limits of the integrals of equations (1), (3), and (4) exist. For simplicity of the exposition we shall limit ourselves to a study of the diffusion in the x-direction only.

If $\nu(x, t)$ is the concentration of a diffusing substance, and k is the molecular diffusivity, then the Fickian equation of molecular diffusion is

$$\frac{\partial \nu}{\partial t} + u(x, t) \frac{\partial \nu}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial \nu}{\partial x}\right). \tag{5}$$

Because of the difficulties of specifying $u(x, t)$, it is convenient to absorb the effect of the turbulent velocity upon the concentration into a so-called eddy diffusivity K. The Fickian equation of diffusivity is then written as

$$\frac{\partial \nu}{\partial t} + U \frac{\partial \nu}{\partial x} = \frac{\partial}{\partial x}\left(K \frac{\partial \nu}{\partial x}\right). \tag{6}$$

Equation (6) is applied frequently in oceanographic problems, and attempts are made to calculate the magnitude of K from observations of U and ν as functions of position and time. It is also possible to express K in terms of the turbulent velocity and a mixing length, following Prandtl. In oceanography it has become customary to think of K as an empirical constant. A knowledge of the eddy diffusivity alone is obviously not enough to determine the turbulent velocity, or the turbulent energy.

If the eddy diffusivity is taken as constant with x and $U = 0$, then the Fickian equation of diffusion (6) takes on the simple form

$$\frac{\partial \nu}{\partial t} = K \frac{\partial^2 \nu}{\partial x^2}. \tag{7}$$

A variety of integrals of this equation is available from the theory of heat conduction. From our point of view, perhaps the simplest is the solution for the diffusion of an instantaneous point source of an amount ν_0 of the diffusing substance, where x_1 is the point at which the instantaneous source was introduced. Since this diffusion is the result of the random motion of the diffusing particles, it is correct to regard the solution above as being indicative of the form of the curve describing the probable separation of a single particle from its starting point. In other words, the probability that a particle at x_1 at $t = 0$ will find itself at x at time t is

$$\frac{1}{\sqrt{4\pi K t}} \exp\left(\frac{-(x - x_1)^2}{4Kt}\right).$$

This notion of probability is important in the theory of diffusion in order to form an intuitive picture of what diffusion really means. It states, in effect, that the future probable position of a *particular* particle is independent of the concentration of neighboring particles $\nu(x)$ (or of $\partial\nu/\partial x$ or $\partial^2\nu/\partial x^2$ for that matter). The important idea to keep in mind is that in simple diffusion there is no "pressure" or "force" which tends

to push particles from regions of greater to regions of lesser concentration. A net flow of particles does occur in such a direction, but merely through the operation of random motion.

We shall now proceed to use this notion of probability for making measurements of the diffusion in the sea.

4. *Failure of the Fickian Equation of Diffusion.* It has been known for some time (Richardson, 1926) that the Fickian equation of diffusion does not apply to the diffusion of clusters in the atmosphere. The question of the applicability of the Fickian equation to diffusion in the ocean may be answered by the following test.

If two particles are placed at time $t = 0$, one at $x = 0$ and the other $x = b_0$, then at time t the probability of the first being at x and the second at $x + b_1$ is, respectively,

$$\frac{1}{\sqrt{4\pi Kt}} \exp\left(\frac{-x^2}{4Kt}\right),$$

and

$$\frac{1}{\sqrt{4\pi Kt}} \exp\left(-\frac{(x + b_1 - b_0)^2}{4Kt}\right).$$

These relations are simply integrals of the Fickian diffusion equation. The probability $P(b_0, b_1)$ that these two particles will be a distance b_1 apart at time t is the product of the two expressions above integrated over all x:

$$P(b_0, b_1) = \frac{1}{2\pi Kt} \exp\left(\frac{-(b_1 - b_0)^2}{4Kt}\right) \int_{-\infty}^{\infty} \exp$$

$$\left(-\frac{1}{Kt}(x^2 + x[b_1 - b_0])\right) dx = \frac{1}{2\sqrt{\pi Kt}} \exp\left(-\frac{(b_1 - b_0)^2}{4Kt}\right).$$

Therefore we see that the Fickian equation of diffusion leads to the result that the probability of a pair of particles a distance b_0 apart along the x-axis being a distance b_1 apart after an interval of time t depends upon $(b_1 - b_0)^2$ only and not upon either b_0 or b_1. The observations of Richardson and Stommel (1948) show that *this conclusion is at variance with the observed facts.* In the ocean the probability of large values of $(b_1 - b_0)^2$ actually increases greatly with b_0 and b_1. The data from the aerial photographs of floats at Woods Hole and Bermuda, discussed later in this paper, also exhibit this discrepancy. There appears to be *no way in which the Fickian diffusion law can be modified to meet this difficulty.*

Sverdrup (1946), in a consideration of the horizontal diffusion of dye spots in the ocean, has suggested that the Fickian equation of diffusion be used with the diffusivity as a linear function of the "average radius" of the spot. C. J. Burke (1946) has analyzed the diffusion of several dye spots over periods up to seven hours and has shown that Sverdrup's suggestion does provide a better fit than the assumption of any constant diffusivity. Although this suggestion is a useful expedient, it does not meet the fundamental difficulties. In a cloud of dye such as that envisaged by Sverdrup the diffusivity (even though it changes with the mean radius of the dye spot) is instantaneously the same everywhere in the cloud, for both close and wide pairs of particles. However, this is contrary to fact. The same objections seem to apply to O. G. Sutton's work (1932) in atmospheric diffusion.

5. *The Search for Another Law of Diffusion.* In molecular diffusion, which is successfully described by the Fickian equation of diffusion, the motion of each molecule is independent of that of its immediate neighbors; but in turbulent fluid flow, neighboring particles of fluids tend to have increasingly similar turbulent velocities as the distance between them is diminished. The reason for this is easily seen if a regime of turbulent eddies of all sizes is contemplated. The distance between two initially close particles will be changed at first only by the smallest eddies, the effect of the large eddies being simply to transport the pair as a whole while not tending to change their separation. However, when the separation of the two particles is larger, the large eddies, in addition to the small ones, can act to change the separation, so that as the separation is increased the dispersing influence of larger eddies is brought into play.

It is important to recognize, when thinking of a turbulent regime of eddies of all sizes, that the meaning of the term eddy is not to be restricted to a simple rotary motion of a certain mass of liquid. The term eddy is frequently used in this limited sense, as may be seen by such terms as "clockwise eddy," the implication being a rotary motion of the fluid in a clockwise sense.

Eddies, although they may be simple rotary motions of a fluid, need not be so. The essential idea of an eddy, as conceived in this paper, is as follows: In the neighborhood of a point of fluid A the particles at a distance α from A will have turbulent velocities to some degree similar to the turbulent velocity of A, and this similarity or local correlation of turbulent velocity extends to some distance $\alpha = \alpha_1$, the quantity α_1 then being thought of as the radius of the eddy.

Richardson (1926) saw that this essential difference between molecular diffusion and the diffusion in a turbulent regime necessitated a

complete reformulation of the equation of diffusion. The important independent variable was not position of a particle but its separation from its neighbors. This necessitated expressing the concentration of a diffusing substance as a function of the mutual separation of the particles of the diffusing substance, not as a function of position. Guided by the form of the Fickian equation, he postulated a new law of diffusion in which the term corresponding to the diffusivity in the Fickian equation was a function of mutual separation.

6. *The Richardson Equation of Diffusion.* The concentration of diffusing substance as a function of position is $\nu(x)$. This may be construed as meaning that there are $\nu(x)dx$ particles of the diffusing substance between x and $x + dx$. If we denote the separation between two particles by l, calling this the "neighbor separation" for convenience, then we can denote the number of particles which have neighbors with neighbor separations of between l and $l + dl$ as $q(l)dl$. The quantity $q(l)$ may be called the "neighbor concentration" in analogy to the concentration. Thus we may express neighbor concentration as a function of the mutual separation of particles rather than as a function of the position of the particles. The mathematical transformation from $\nu(x)$ to $q(l)$ is accomplished in the following way:

$$q(l) = \int_{-\infty}^{\infty} \nu(x)\, \nu(x + l)\, dx\,.$$

The equation of diffusion which Richardson postulated is

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial l}\left[F(l)\,\frac{\partial q}{\partial l}\right],$$

which is analogous to the Fickian equation, but with neighbor separation replacing position as the independent variable. The quantity $F(l)$ is analogous to the diffusivity K of the Fickian equation and may be called the "neighbor diffusivity" in order to distinguish it from the ordinary diffusivity of Fick. Because $F(l)$ is a function of l, it is possible to reconcile it with the observed facts. This, indeed, is the whole reason for the transformation from x to l as independent variable.

From a large number of observations with different values of l in the atmosphere, Richardson (1926) induced that the neighbor diffusivity is of the form

$$F(l) = \varepsilon l^{4/3}$$

in the air, where ε is a constant. This equation will be spoken of frequently as the "4/3 law."

The observations of Richardson and Stommel (1948) and the data from aerial photographs of floats at Woods Hole and Bermuda suggest that this law is generally operative in the diffusion of material in the ocean.

Although both neighbor diffusivity $F(l)$ and eddy diffusivity K have the same dimensions, it is clear that in general they are in no direct way comparable, for both are functions of different variables and are defined by different equations. However, in certain special cases it is possible to argue from the magnitude of one to that of the other. A discussion of this comparison is given in some detail in Richardson's (1926) paper. In the special case where $F(l)$ is independent of l, $F = 2K$. In the special case where the 4/3 law holds, that is, where $F(l) = \epsilon l^{4/3}$, it is possible to get a rough idea of the comparison of K. Then $F(l) \backsimeq 3.03\ K$.

7. *A Method for the Determination of the Neighbor Diffusivity as a Function of the Neighbor Separation.* In a previous section we saw that the Fickian diffusion equation predicted that the probable change of separation of two floats did not depend upon the separation itself. This result was contrary to observed fact. We shall now make use of observations of this sort to indicate a method for determining the neighbor diffusivity as a function of the neighbor separation.

If floats are released in pairs at a fixed initial separation l_0 apart, and if the separation l_1 is measured again after a time interval T which is small enough so that $l_1 - l_0$ averages only a small fraction of l_0, it is seen that the scale will be practically the same for the observation of each pair. The Richardson equation of diffusion may then be written in the following form:

$$\frac{\partial q}{\partial t} = F(l_0)\,\frac{\partial^2 q}{\partial l^2}.$$

A solution of this equation is

$$q(l_1) = \frac{\text{const.}}{\sqrt{T}} \exp\left[-\frac{(l_1 - l_0)^2}{4TF(l_0)}\right],$$

which shows the distribution of $q(l_1)$ about the mean separation at time T. Of course at time $t = 0$ the entire population is at a separation l_0. The standard deviation of l_1, from the mean l_0, is $\sqrt{2TF(l_0)}$; therefore the neighbor diffusivity is given for the value l_0 by the following equation, where the bar denotes mean of all pairs:

$$F(l_0) = \frac{\overline{(l_1 - l_0)^2}}{2T}.$$

In practice the l_0 for each pair will not be identical, so it will be necessary to compute a mean of the type $\frac{1}{2}\overline{(l_1 + l_0)}$ as a measure of the scale.

$$F(\tfrac{1}{2}\overline{(l_1 + l_0)}) = \frac{\overline{(l_1 - l_0)^2}}{2T}$$

This equation is the one used in the reduction of the data observed in this paper. Many pairs were dropped into the water at different places simultaneously, so that from the photograph the various pairs are chosen at random in groups of approximately equal $\frac{1}{2}(l_1 + l_0)$. The quantities $\overline{\frac{1}{2}(l_1 + l_0)}$ and $\overline{(l_1 - l_0)^2}/2T$ are computed for each of these groups separately, each group giving a value of $F[\overline{\frac{1}{2}(l_1 + l_0)}]$ for a particular neighbor separation.

8. *Methods of Observation at Sea.* The observations of Richardson and Stommel were very restricted in range of scale and were made in only one Scottish Loch. For universal application to the ocean these observations need to be repeated widely, and the range of scales must be greatly extended to include much greater distances. In the following paragraphs suggestions are made for methods of observation on various scales.

9. *The Scale from 10 M. to 1 Km.* Aerial photography of suitable floats answers best in this range, the floats being so submerged as to avoid the direct stress of the wind.

A number of ideas suggested themselves to this end. At first the use of fluorescein dye in water soluble form, distributed over the ocean surface in spots, seemed to be best. There could be little doubt that the motion of the dye and the water would be identical—at least in the horizontal direction. Two methods were used for dispersing the dye: (1) dropping it in cardboard ice cream containers which burst upon striking the water, leaving easily discernible splotches, and (2) introducing the dye directly into the ocean with a hose from a slow-moving surface ship. The greatest difficulty with the dye spots was judging the centers, errors of judgment in this respect being particularly bad for determination of neighbor diffusivity for small neighbor separations. In addition, the spots of dye themselves diffused and became indistinct so rapidly that they were no longer measurable in the time required for appreciable motions of wide pairs. This placed an upper limit on the neighbor separation as well.

It then occurred to the writer to try meteorological balloons, brightly colored and inflated with sea water instead of air. Enough fresh water could be added to balance the weight of the rubber itself so that

Figure 1. Two batches of paper floats diffusing on the sea surface. The boat gives a measure of the scale of the phenomenon.

the balloons floated just below the surface, the wind thus having little effect upon them. They were so heavy, however, that it was necessary to inflate them in the sea (handling them with fish-nets), and since the pumps available did not have a great capacity it took too long to inflate enough balloons to make a profitable series of photographs. However, the balloons were clearly visible and possibly the technique could be used for other purposes.

The most promising type of float was suggested by Dr. R. B. Montgomery—namely pieces of paper. The writer tried various kinds of paper from a skiff, and it appears that standard mimeograph paper answers well, this being sufficiently absorbent to become quickly wetted yet light enough to float. Several hundred sheets of such paper may be dropped from the airplane at an altitude of a hundred feet; they immediately scatter in the air, and upon striking the water surface they make a well defined pattern of points which may be photographed. Fig. 1 shows such a pattern of papers scattered on the sea surface.

10. *The Scale from 1 Km. to 1000 Km.* Large scales might be investigated by the use of long range sound transmission techniques in places where the detection stations are already established. Small floats, containing from two to five explosive pressure detonated charges which are dropped successively, could be set at wide distances apart on the sea surface from steamers in the regular lanes. The positions of the explosions might then be determined by the standard triangulation procedure.

The bombs could be released by salt blocks, a small compensating float being released with each bomb to preserve the trim of the remaining apparatus.

11. *General Remarks on the Observation of Floating Pairs.* Since the turbulent exchange is to be determined as a function of the scale of the phenomenon, it is important that the time interval between successive observations of the same pair be small enough so that the scale is not significantly altered between observations. On the other hand, the time interval should be large enough to avoid the influence of the observational errors in the distance measurements. The time interval of 30 seconds, employed in the observations of Richardson and Stommel (1948), was rather too large. A rough indication of the time intervals desirable for different scales may be obtained from the assumption that the preceding theory is correct. The following table was computed in this fashion and should give an indication of the time intervals that are likely to be useful.

Scale l_0	*Time interval between successive measurements, T*
10 cm	5 sec
1 m	25 sec
10 m	2 min
100 m	7 min
1 km	40 min
10 km	3 hr
100 km	12 hr
1000 km	3 days

A careful examination of the errors of observation must be made for any method of observation adopted, since random errors will have the effect of increasing the value of the turbulent exchange.

12. *Observations: Blairmore, Woods Hole, Bermuda. Blairmore*—The first observations made in the ocean for the purpose of testing the 4/3 law were those of Richardson and Stommel (1948), quoted here: "In the sea we used floats of parsnip because it is easily visible, and because it is almost completely immersed so as not to catch the wind which, moreover, was slight. The floats were about 2 cm in diameter. An optical device was used for measuring the distance l in a fixed azimuth. The observations were made in latitude 56° 0′ N, longitude 4° 54′ W from Blairmore Pier, Loch Long, Scotland, on 6 January 1948, where the sea water was about two meters deep. In order to eliminate any change in $F(l)$ with time, we observed alternately with large and small l. The function $F(l)$ was computed separately for the wide and close pairs":

	Wide pairs	*Close pairs*	*Unit*
l	187.7	26.7	cm
$F(l)$	84.3	6.4	$cm^2\ sec^{-1}$

Woods Hole—A number of observations of the diffusion of floats were made in Vineyard Sound near Woods Hole. Some of these were not successful for a variety of reasons, such as difficulty with the camera or an insufficient number of floats. Of the half dozen series of observations, two are chosen as being fairly representative.

Series 1: Dye spots were introduced into the water by means of a hose from a slow-moving boat. A wooden frame-work was floated in the water so that it would also appear in the photographs and thus provide an accurate scale for each picture. The depth of water was about 25 m, and a strong tidal current prevailed. The time interval was 2 min.

Close pairs:		*Wide pairs:*	
l_0	l_1	l_0	l_1
cm	cm	cm	cm
1450	1040	9500	8500
1540	1670	9200	8400
1805	1670	9500	6900
2450	1990	7400	8600
1370	1350	11600	10350
2140	1840		
2120	2150		
2120	2150		
1820	2130		
1660	1920		
2320	1990		
1820	1680		

In addition to the observations of the motion of pairs of dye spots, there was the diffusion of the dye in the spots themselves which gave a rough approximation of the diffusion on even a smaller scale. For this purpose one may compute the ordinary diffusivity K and then convert it to $F(l)$ by multiplying by 3.03, although admittedly this is not a completely satisfactory or strictly logical procedure. In this way the following table was computed:

	Wide pairs	*Close pairs*	*Diffusion of a single spot*	*Units*
l	9000	1800	290	cm
$F(l)$	2400	120	50	$cm^2\ sec^{-1}$

Series 2: Pieces of mimeograph paper were dropped from an airplane in Vineyard Sound off the Falmouth Beach in about 4 to 10 meters of water. There was a very strong tidal current. From the air, clouds of sediment, stirred up from the bottom, could be seen. The time interval was 80 secs.

Close pairs:		*Wide pairs:*	
l_0	l_1	l_0	l_1
cm	cm	cm	cm
61	102	466	353
87	22	466	493
105	29	484	210
61	61	448	492
79	61	353	529
87	51	475	598
123	95	448	407
123	73	456	368

Close pairs:		*Wide pairs:*	
l_0	l_1	l_0	l_1
cm	cm	cm	cm
96	44	456	456
87	44	353	370
87	80		
52	86		
87	44		
96	87		
87	114		

The reduction of these observations leads to the following values:

	Wide pairs	*Close pairs*	*Unit*
l	430	77	cm
$F(l)$	92	10.4	$cm^2\ sec^{-1}$

Bermuda—A typical series of measurements from aerial photographs off Bermuda in deep water is given in the following table. The water was about 2,000 meters deep.

Five Miles SE of Cataract Hill, Bermuda, November 22, 1948

Close pairs:		*Wide pairs:*	
l_0	l_1	l_0	l_1
cm	cm	cm	cm
111	91	600	585
66	80	840	695
66	128	870	951
45	131	690	805
69	146	810	329
45	0	810	768
81	201	1050	1207
75	110	990	1299
114	146	540	480
84	219	810	1006
150	36	750	860
150	201	915	256

The reduction of these measurements leads to the following values:

	Wide pairs	*Close pairs*	*Unit*
l	795	103	cm
$F(l)$	337	36	$cm^2\ sec^{-1}$

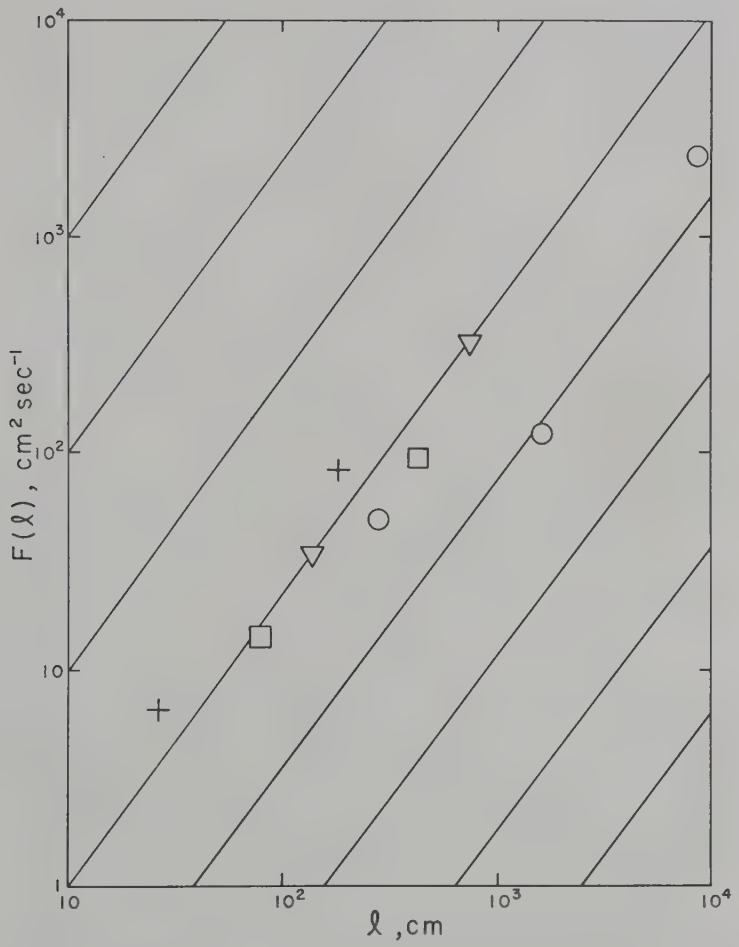


Figure 2. Data plotted for measurements given in the text. The crosses are for data obtained at Blairmore; circles, Woods Hole, Series 1; squares, Woods Hole, series 2; triangles, Bermuda.

13. *Summary of Observations.* The values of the neighbor diffusivity are plotted against the neighbor separation (for the observations listed) in Fig. 2. Lines are drawn on these graphs to show the direction of

the 4/3 slope. The constant of proportionality ε is not the same for all the graphs.

The data plotted seem to justify the supposition that the 4/3 law is satisfied. If the classical Fickian law were obeyed, the points for any particular set of observations would have equal $F(l)$ instead of an increase with l.

II. DEDUCTIVE METHODS

14. *Introduction.* The observational methods of studying ocean turbulence, as described in the first part of this paper, were based upon an attempt to find a law of diffusion which fitted the observed facts. The method involved a number of theoretical ideas, all inductive in nature. The result of this process was the rejection of the Fickian law of diffusion and the introduction of the Richardson law. The observations confirm the discovery that in the ocean, as well as in the atmosphere, the neighbor diffusivity of fluid particles is proportional to the 4/3 power of the neighbor separation measured along a fixed azimuth.

We now turn to a completely different mode of study, in which the energy decay of large scale motions of a fluid is examined, the method being a deductive one based on von Weisaecker (1948) and Heisenberg (1948). The remarkable result emerges that in turbulent regimes of large Reynolds number the eddy viscosity obeys a closely analogous 4/3 law. This deduced result is entirely independent of the previous inductive approach.

15. *The Necessity of a Spectrum of Eddies in the Ocean.* The semi-permanent wind systems, such as the trades and the prevailing westerlies, impart large scale motions to the ocean surface layers by virtue of the frictional stress of the wind acting upon the water. The source of energy of the large scale ocean currents, such as the Equatorial Currents, is explained in this way. The stress of the wind, working upon the ocean water, tends to increase its kinetic energy. However, the mean kinetic energy of the ocean currents remains fairly constant, so that on the whole as much energy must be dissipated into heat as is gained from the work done by the wind stress. Molecular viscosity alone is insufficient to dissipate enough kinetic energy to act as an effective brake upon the major ocean currents. However, ocean currents break up into eddies, which in turn degenerate into smaller eddies, and so on, until eddies are formed that are of a size sufficiently small to be dissipated irreversibly by molecular viscosity into heat energy. The exact dynamical explanation of the cause of the breakdown of the ocean currents into eddies of various sizes is yet to be

formulated, but the empirical fact of their existence is not disputed (Iselin and Fuglister, 1948; Spilhaus, 1940). The existence of an entire "spectrum" of eddies is apparently necessary as an agency capable of dissipating the kinetic energy of the ocean currents that is supplied by the stress of the wind.

The completely detailed field of motion in the ocean is therefore exceedingly complicated, constantly changing with time and defying minute description in much the same way as the individual molecular motions of a liter of air.

The eddy motion of fluids in flumes and wind tunnels has been treated in a statistical fashion (Taylor, 1935, 1938; Dryden, 1943), but until recently there has been no similar attack upon the problem of the large scale motions of the atmosphere and ocean.

In practical oceanography it has long been recognized that the term "velocity," when applied to an ocean current, always involves a mean over a certain time interval or volume, or both, depending on the method of observation employed. For example, the determination of currents from a compilation of the drift of ships involves an averaging of velocity over at least several hours and scores of miles. Another oceanographic example is the determination of a velocity field by the standard method of dynamic computations, in which the spacing of the hydrographic stations defines the scale of the averaging; the velocities obtained are averages over the distance between successive stations. A picture of the velocities determined in this manner lacks the finer scale features which are present. Therefore, it is important to recognize that *the term "velocity" is meaningless unless accompanied by some indication of the mode of averaging employed in its determination.*

Once the mode of averaging has been decided, the velocity field has a meaning. The components of water motion that occur on a scale smaller than that used in the velocity averaging process do not appear in this "average velocity field," but they do exert an influence upon the dynamics of the average velocity field as Reynolds stresses. The Reynolds stress involves a quantity known as the eddy viscosity which depends upon the mode of averaging. In other words, *the term eddy viscosity is meaningless unless accompanied by some indication of the mode of averaging employed in its determination.*

16. *Recent Theoretical Studies of Turbulence at Large Reynolds Number.* During the war years the fundamental nature of turbulence was temporarily neglected. However, three remarkable papers appeared quite independently which shed light on the spectrum of turbulence at large Reynolds numbers. The first of these was by A. N. Kolmogoroff (1941) of Russia; in the original form, these Kolmogoroff papers were

extremely condensed, so that Batchelor (1947) was led to discuss the theory at some length to make it available to investigators in general. The second paper was by L. Onsager (1945) in the United States. The third in this remarkable series was by the German astrophysicist, C. F. von Weisaecker (1948), whose ideas have been developed and elaborated by Werner Heisenberg (1948). With certain modifications of a minor kind, such as those indicated by the writer, these theories may prove to be valuable in getting at a clearer picture of the spectral distribution of energy in the turbulence of the ocean. First we shall introduce certain hypotheses about the eddies in the ocean which lead to the Weisaecker-Heisenberg development. Then we shall reexamine these hypotheses in the light of actual facts—*so far as we know them*—to see how they must be modified for a closer fit to things as they are. This latter process will be particularly valuable because it will point out where our empirical ignorance lies and where observational material is desperately needed.

17. *The Weisaecker-Heisenberg Theory.* Suppose that in the ocean we could take as premises:

Hypothesis 1. There exists a continuous series of eddies of all sizes which are horizontally isotropic; that is, the quadratic time mean square of the velocity is independent of choice of co-ordinate direction.

Hypothesis 2. A constant supply of kinetic energy is available to the large eddies (ocean currents driven by wind stress).

Hypothesis 3. This energy sifts down to smaller eddies.

Hypothesis 4. The smallest eddies lose their energy into heat energy.

Can we now discover, on the basis of these hypotheses, from the equations of viscous flow and continuity:

(1) How the energy is distributed over eddies of different size (that is, the spectrum of turbulence)?

(2) In what manner the average velocity is dependent upon the mode of averaging?

(3) In what manner the eddy viscosity is dependent upon the mode of averaging?

The work of Weisaecker and Heisenberg makes it possible to give answers to these questions provided an additional hypothesis is introduced, the nature of which will be shown when it is introduced.

In this section we adapt the Weisaecker argument to lateral turbulence in the sea, where it is more natural (except for the smallest scales) to average over surface areas than over volumes. We shall need to average over a wide variety of size areas.

The largest area may be taken as a square of side L_0. Suppose that this area is divided into smaller squares of side L_1, where $L_0 = rL_1$.

Each of these squares is divided into smaller squares of side L_2, and so on, the process being repeated according to the formula

$$L_n = rL_{n+1}\,, \tag{1}$$

where r is some positive integer independent of n. The scale—finer as n increases—is represented by the quantity L_n, and an average over a square of side L_n may be spoken of as the n-th mode of averaging.

Let the x-component of the velocity be u and the y-component be v. We may divide these velocities into a sum of terms such as follows:

$$\begin{aligned} u &= u_0 + u_1 + u_2 + \ldots \\ v &= v_0 + v_1 + v_2 + \ldots, \end{aligned} \tag{2}$$

with the subscript quantities defined as follows:

$$\begin{aligned} u_0 &= \text{average of } u \text{ over square } L_0 \\ u_1 &= \text{average of } (u - u_0) \text{ over square } L_1 \\ u_{n+1} &= \text{average of } (u - U_n) \text{ over square } L_{n+1} \end{aligned} \tag{3}$$

where $U_n = \sum_{m=0}^{m=n} u_m$. Since u_n is a function of time with a definite root time mean square, this is denoted by

$$\overline{U_n} = \sqrt{\lim_{T\to\infty} \frac{1}{T}\int_0^T (U_n)^2\, dt}\,. \tag{4}$$

It is convenient to define another quantity, $\mathbf{u}_n$, in the following manner:

$$\mathbf{u}_n = \sum_{m=n+1}^{m=8} u_n\,. \tag{5}$$

The total velocity u may then be written

$$u = U_n + \mathbf{u}_n\,, \tag{6}$$

where, with respect to the n-th mode of averaging, U_n is the average velocity and $\mathbf{u}_n$ the turbulent components. Depending upon the particular mode of averaging (value of n), the values of U_n and $\mathbf{u}_n$ are different. If we introduce time averages as in equation (4), the equation (2) may be rewritten in the following manner:

$$\bar{u} = \overline{U_n} + \overline{\mathbf{u}_n}\,. \tag{7}$$

In a similar manner averages of the derivatives may be denoted

$$\frac{\partial u}{\partial x} = \left(\frac{\partial u}{\partial x}\right)_0 + \left(\frac{\partial u}{\partial x}\right)_1 + \ldots\,. \tag{8}$$

We denote

$$\overline{u_n'} = \sqrt{\lim_{T \to \infty} \int_0^T \left(\frac{\partial u}{\partial x}\right)_n^2 dt}\,. \tag{9}$$

It is necessary to discover some relation between $\overline{u_n}$ and $\overline{u_n'}$, and for this purpose we write the formal relation

$$\overline{u_n'} = \alpha \overline{u_n}/L_n\,. \tag{10}$$

We now find it necessary to introduce an hypothesis:

Hypothesis 5: The eddy motion is kinematically similar; this requires that all statistical characteristics of turbulence are independent of the absolute linear dimensions.

Therefore, α is independent of n.

The energy dissipation per unit time and unit volume is

$$S = \mu \left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 \right], \tag{11}$$

in which μ is the molecular viscosity. If μ_n is introduced as the time average turbulent exchange, equation (11) may still be used. The turbulent exchange μ_n depends upon $\overline{\mathbf{u}_n}$ and may be written formally in the way Prandtl introduced it,

$$\mu_n = \rho\, l_n\, \overline{\mathbf{u}_n}\,, \tag{12}$$

where l_n is the "mixing length" of the n-th mode of averaging. The quantity l_n is defined in terms of L_n by

$$l_n = \beta L_n\,, \tag{13}$$

where, by Hypothesis 5, β is independent of n. Because of the isotropy introduced by Hypothesis 1, equation (11) becomes

$$S_n = \mu_n\, 8 \sum_{m=0}^{m=n} (\overline{u_m'})^2. \tag{14}$$

Now, S_n must be independent of n because the flow of energy cannot depend upon a division into average and turbulent flow. Quite formally we write

$$u_{n+1} = \xi\, u_n\,, \tag{15}$$

where $\xi < 1$ and is independent of n by Hypothesis 5. Therefore, $\overline{\mathbf{u}_n}$ may be replaced by the following identity:

$$\overline{\mathbf{u}_n} = \frac{\xi}{1 - \xi}\, \overline{u_n}\,. \tag{16}$$

Substituting from equation (10) into (14),

$$S_n = 8\mu_n \alpha^2 \sum_{m=0}^{m=n} \left(\frac{\overline{u_m}}{L_m}\right)^2, \tag{17}$$

and by virtue of (15) this may be summed to

$$S_n = 8\mu_n \alpha^2 \left(\frac{\overline{u_n}}{L_n}\right)^2 \frac{(\xi r)^2}{(\xi r)^2 - 1}, \tag{18}$$

and from equations (12), (13) and (16)

$$S = \Gamma \frac{\overline{u_n}^3}{L_n}, \tag{19}$$

where

$$\Gamma = 8\rho\beta\alpha^2 \frac{\xi}{1 - \xi} \frac{(\xi r)^2}{(\xi r)^2 - 1} \tag{20}$$

is independent of n. This is von Weisaecker's result. Therefore the spectral law for velocity is the following:

$$\overline{u_n} \propto L_n^{1/3}. \tag{21}$$

The spectral law for eddy viscosity is as follows:

$$\mu_n \propto L_n^{4/3}. \tag{22}$$

The spectral law for energy is as follows:

$$\overline{E_n} \propto L_n^{2/3}. \tag{23}$$

In discussing the spectral laws, von Weisaecker used a discrete spectrum, but Heisenberg has elaborated this technique and extended it to cover a continuous series of modes of averaging.

18. *Critique of the Applicability of the Weisaecker-Heisenberg Theory to the Ocean.* It is important to examine the hypotheses of the Weisaecker-Heisenberg theory in the light of how they bear upon the application of the theory to the turbulence in the ocean.

First of all, the semipermanent wind systems, though of primary importance, are not the only cause of water motion. Local winds supply energy to smaller scale eddy systems, and so do local tidal currents. In addition, thermal convection in the surface layers may play a role at certain levels of the eddy spectrum. These secondary sources of kinetic energy prevent the dissipation S_n from being entirely independent of n, rather making S_n increase with n. To the extent that these effects enter, Hypotheses 2 and 3 must be altered.

Hypothesis 1 is certainly not true for the real ocean. That there is a spectrum of eddies is not disputed, but the supposition that they are horizontally isotropic is open to question, particularly for the large size eddies. Certainly for the largest eddies—the major ocean currents—there is no isotropy at all. If the initial mode of averaging $n = 0$ is taken, so that L_0^2 is approximately the area of the ocean (for example, the North Atlantic Ocean), it is clear that for $n = 0, 1, 2$, up to some value $n = p$ at least, Hypothesis 1 cannot apply. Whether Hypothesis 1 applies in the actual ocean for n greater than p is a question that must be answered by observation. This is really a result in itself, because it points out the need for and the nature of certain types of current observation at sea. We may venture to introduce an alternate hypothesis which is more likely to be applicable to the ocean but which is as yet not thoroughly tested by observation.

Hypothesis 1′: The series of eddies in the ocean is horizontally isotropic for modes of averaging for which n is greater than p, but not necessarily so for $n \leqslant p$.

The Hypotheses 2, 3, and 4 apply to the ocean as it actually is. Hypothesis 5 must be replaced by another in the following fashion.

Hypothesis 5′: The eddy motion is kinematically similar for $n > p$.

On the basis of these slight changes in hypotheses, we introduce

$$\overline{\mathcal{U}_p} = \overline{u_0} + \overline{u_1} + \ldots \overline{u_p}\,, \tag{24}$$

where $\mathcal{U}_p$ is the sum of the large size averaging components of velocity which do not fulfill the restrictions of isotropy and kinematic similarity. Equation (2) may then be written in the following form:

$$\bar{u} = \overline{\mathcal{U}_p} + \overline{u_{p+1}} + \overline{u_{p+2}} + \ldots \tag{25}$$

Quantities such as $\overline{U_n}$ and $\overline{\mathbf{u}_n}$ still retain their meanings, but the summation processes cannot be carried out for all n. The independence of α and β of n holds only for those $n > p$. It will be helpful also to define another quantity $\overline{U}_{p,n}$ similar to $\overline{U_n}$ but in which the range of summation extends from $m = p + 1$ to $m = n$,

$$\overline{U}_{p,\,n} = \sum_{m=p+1}^{m=n} \overline{u_m}\,. \tag{26}$$

Therefore,

$$\bar{u} = \overline{\mathcal{U}_p} + \overline{U}_{p,n} + \overline{\mathbf{u}_n}\,. \tag{27}$$

This equation illustrates clearly the meanings of the various terms from a physical point of view. The rms (quadratic time mean square)

point velocity is regarded as being made up of three parts, each of which is a sum over a certain range of the spectrum of turbulence. The first term represents the sum of the rms velocities of the anisotropic, kinematically dissimilar largest scale horizontal motions; the second term is the sum of the rms velocities of the isotropic, kinematically similar horizontal eddies down to and including the n-th mode of averaging; the third term is the sum of the eddy rms velocities smaller than n-th mode of averaging. The first two terms are, from the point of view of the n-th mode of averaging, the "average velocity" of the fluid and the third term contains the turbulent fluctuations of the velocity.

19. *Kolmogoroff's Theory of Locally Isotropic Turbulence: The Eddy Cascade.* The theory of Weisaecker (1948) and Heisenberg (1948) was anticipated by A. N. Kolmogoroff (1941) of Russia, but the form in which it was written was analytically quite different, so that the immediate connection of Kolmogoroff's work with the type of observation on diffusion of clusters described in Part I was not evident to the writer. It was only after the writer had seen the manuscript of Weisaecker that he saw the connection; then later, when he came across the paper of Batchelor (1947), the fact that Kolmogoroff had been treating the same problem was made clear.

Kolmogoroff treats the correlations of the differences of parallel velocity fluctuations at two points in a certain domain G in which the turbulence is isotropic and statistically steady. This is insured by choice of domain G and by placing an upper bound upon r, the distance between the two points. Now, supposing that the Reynolds number of the flow as a whole is very large (as it is in natural bodies of fluid like the ocean), Kolmogoroff introduces two similarity hypotheses:

(1) The statistical characteristics of the turbulent flow are functions of the molecular viscosity and the mean energy dissipation per unit mass of the fluid only.

(2) The statistical characteristics of the large eddies depend upon the mean dissipation of energy per unit mass of the fluid only.

Batchelor (1947) finds that these two hypotheses hold reasonably well in the turbulence of a wind tunnel. The observations given in Part I of this paper seem to indicate that the hypotheses hold for the ocean as well.

From these hypotheses Kolmogoroff then proceeded to show by a dimensional argument that the double parallel velocity correlation is of the form $1 - Ar^{2/3}$, where A is a constant and r is limited to a certain middle range. This equation is similar to Heisenberg's (1948) equation 57.

20. *Onsager's Theory of the "Violet Catastrophe."*[3] The theory of L. Onsager (1945), published in abstract only, has much in common with the other two theories. It, too, deals with turbulent flow in which the Reynolds number of the entire motion is indefinitely large, in which molecular viscosity has little influence except near $r = 0$, in which the energy of each size eddy comes from larger ones and is dissipated into smaller ones until the smallest eddies are reached, which are laminar and dissipate their energy into heat via molecular viscosity. Onsager starts by describing the turbulent regime in terms of three-dimensional Fourier series. From the equations of mean motion he is able to determine the transfer of kinetic energy from one wave-length velocity component to another, determining the distribution of energy with wave-length. He then uses the Fourier transform to obtain (Taylor, 1938) the correlation coefficient which agrees in form with that found by Kolmogoroff.

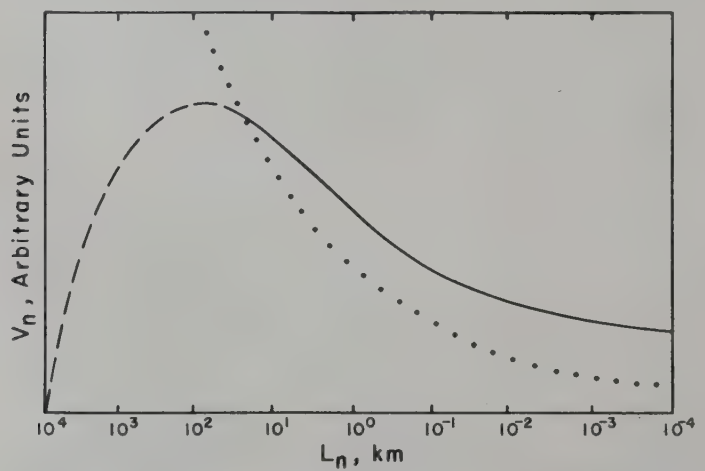


Figure 3. The solid line is a hypothetical spectrum of the root mean square turbulent velocity in the ocean. The dashed portion on the curve is the more uncertain portion of the hypothetical spectrum. The dotted line is the pure Weisaecker-Heisenberg theoretical spectrum.

21. *Hypothetical Spectrum of Turbulence in the Deep Ocean.* Presumably the velocity spectrum of turbulence at a point in the deep

[3] So-called because all kinetic energy degenerates toward the short end of the spectrum.

ocean will look something like Fig. 3. The scale of the ordinates is linear but in arbitrary units, a constant factor being indeterminate until observed values of the intermediate scales are available. The left-hand portion of the curve is dashed to indicate that it is particularly uncertain due to the anisotropy and kinematic dissimilarity it exhibits. It is important to remember, in considering this hypothetical picture, that the Weisaecker-Heisenberg theory applies only to that part of turbulent energy descending from large scale systems. The additional effects of local winds, bottom friction, and of irregularities in the bottom, are not taken into account in the Weisaecker-Heisenberg approach, which, after all, is hardly to be expected. Inshore localities and tideways exhibit turbulence of a local nature, but even this turbulence, in the middle range, appears to follow the 4/3 law, as is shown by the Blairmore and Woods Hole observations.

The right-hand portion of the curve is drawn with slightly less negative slope than the Weisaecker-Heisenberg theory in order to indicate that energy is also received by the ocean from sources other (local winds) than descent from the large scale motions.

22. *Summary.* As explained in the prefatory abstract, this paper represents a synthesis of two independent methods of approach in the study of turbulence and turbulent diffusion as applied to the ocean. The first part of this paper, dealing with inductive methods, stands quite by itself, supported as it is by observation. It represents a marked departure from ordinary notions of diffusion in the sea. The second part of this paper, summarizing the deductive theories of locally isotropic turbulence, is more abstract, less substantiated by observation; however, since it fits so well as a possible mechanism which explains the somewhat anomalous behavior of a turbulent regime as induced from the first part, it seems well worth considering when we turn attention to the details of the turbulent motion which is producing the diffusion in question.

It is always tempting in preparing a techical paper to refrain from discussing unsettled questions, in this way giving the finished product a polished appearance. Had this been the goal, the first part alone would have been enough by itself, with a new law of diffusion for the sea and observations to support it. But one inevitably inquires as to the "why" of this new law of diffusion, and in so doing must refer to the nature of the turbulent regime itself. This naturally leads to questions about the various scales of turbulence in the ocean dealt with in the second part of this paper. By a happy coincidence, investigators in other branches of fluid mechanics have already begun to study the spectrum of turbulence at large Reynolds number, or as it is altern-

atively called, the "eddy cascade" and the "violet catastrophe." The immediate applicability of these notions to the sea is controversial, but oceanographers should consider them seriously.

And finally, what is the value of studies such as these, other than any practical application of the diffusion law? The writer thinks there is a question of morale. At present oceanographers recognize that there is no perfectly simple circulation in the ocean, that currents are not clearly defined rivers in the sea, and that even the Gulf Stream wanders and meanders, so that the more closely one looks at it the more bewildering it is. In fact, there seems to be no means of achieving a sharply focused picture in the study of the ocean currents. What appeared yesterday as a smooth broad stream appears today as an amazingly corrugated irregular one, and tomorrow probably even finer details of greater complexity will make an appearance. So the oceanographer is assailed by growing doubts as to whether or not he can ever hope to describe the details with any meaning. The Weisaecker-Heisenberg theory shows in principle, at least, how such a description can be made in the language of the statistical theory of turbulence. Therefore it is a useful tool in thinking about the ocean's motion.

REFERENCES

Batchelor, G. K.
1947. Kolmogoroff's theory of locally isotropic turbulence. Proc. Camb. phil. Soc., *43:* 533–539.

Burke, C. J.
1946. Horizontal diffusion of dyes in the ocean. Oceanogr. Rep. Scripps Instn. Oceanogr., No. 2. Unpublished.

Dryden, Hugh
1943. A review of the statistical theory of turbulence. Quart. appl. Math., *1* (1): 7–42.

Heisenberg, W.
1948. Zur statistischen Theorie der Turbulenz. Z. Phys., *124:* 628–657.

Iselin, C. O'D. and F. C. Fuglister
1948. Some recent developments in the study of the Gulf Stream. J. Mar. Res., *7* (3): 317–329.

Kolmogoroff, A. N.
1941. C. R. Acad. Sci. U. R. S. S., *30* (4); *31* (6); *32* (1).

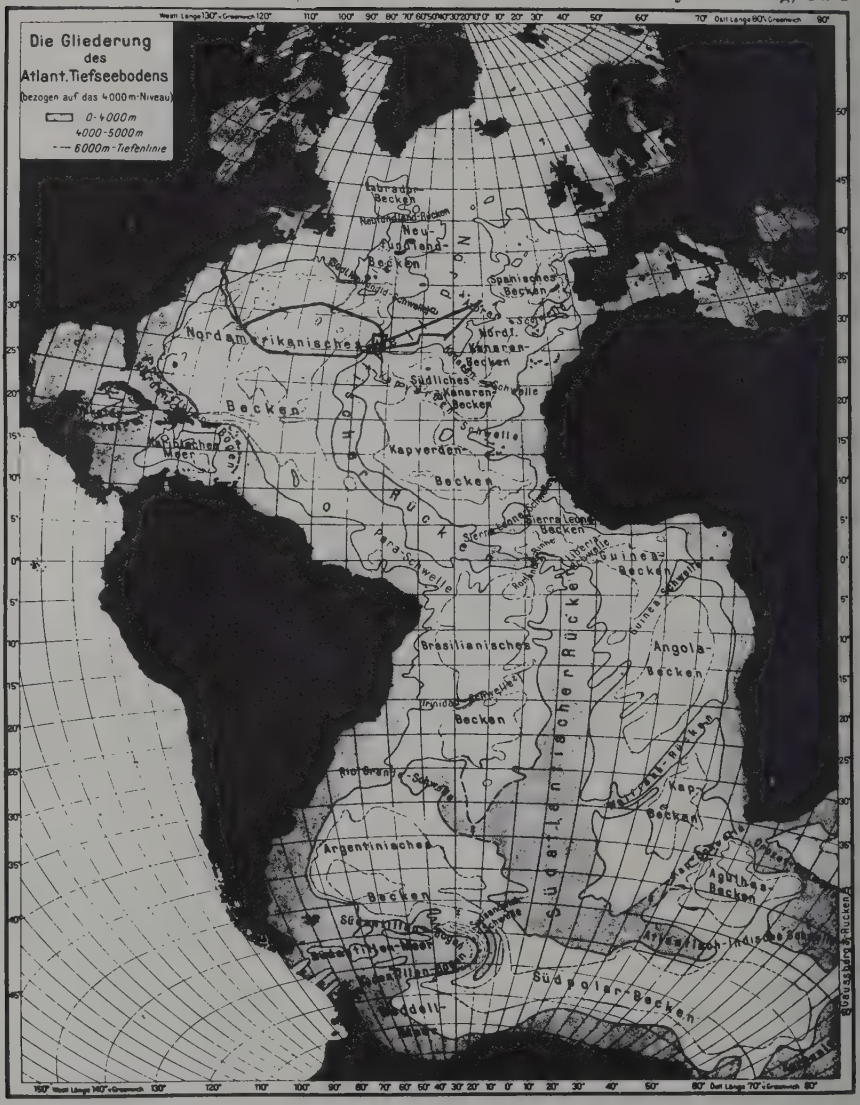
Onsager, Lars
1945. The distribution of energy in turbulence. Phys. Rev., (2) *68:* 286 (Abstr.).

Richardson, L. F.
1926. Atmospheric diffusion shown on a distance-neighbour graph. Proc. roy Soc., (A) *110:* 709–727.

Richardson, L. F. and Henry Stommel
1948. Note on eddy diffusion in the sea. J. Meteorol., *5:* 238–240.

Spilhaus, A. F.
1940. A detailed study of the surface layers of the ocean in the neighborhood of the Gulf Stream with the aid of rapid measuring hydrographic instruments. J. Mar. Res., *3* (1): 51–75.
Sutton, O. G.
1932. A theory of eddy diffusion in the atmosphere. Proc. roy. Soc., (A) *135:* 143–165.
Sverdrup, H. U.
1946. Speculations on horizontal diffusion in the ocean. Oceanogr. Rep. Scripps Instn. Oceanogr., No. 1. Unpublished.
Taylor, G. I.
1935. The statistical theory of turbulence. Introduction and Summary of Parts I–IV. Proc roy. Soc., (A) *151:* 421–454.
1938. The spectrum of turbulence. Proc. roy. Soc., (A) *164:* 476–490.
Weisaecker, C. F. von
1948. Das Spectrum der Turbulenz bei grossen Reynoldsschen Zahlen. Z. Phys., *124:* 614–627.

Contribution No. 498



THE ATLANTIC OCEAN, AFTER MAURER AND STOCKS

The path of the ATLANTIS during the summer of 1947 (Cruise 150) is shown by the black lines

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 60, PP. 1527–1540 8 PLS., 4 FIGS. OCTOBER 1949

NORTH ATLANTIC HYDROGRAPHY AND THE MID-ATLANTIC RIDGE

By Ivan Tolstoy and Maurice Ewing

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Abstract

This paper presents primarily the soundings obtained by the Research Vessel Atlantis during the summer field season of 1947. It also utilizes some of the data obtained by later expeditions of the Atlantis and by several other vessels. The Atlantis is equipped with a continuously recording fathometer with a range up to 4000 fathoms.

The outstanding features of the area investigated in 1947 (Atlantis cruise #150) are:

(1) A conspicuously flat plain at a depth of 2900 fathoms occupies the deeper sections of the North Atlantic basin between Bermuda and the Azores. More recent data indicate that this horizontal stretch of sea floor extends at least as far south as Lat. 29°N. and possibly as far north as Lat. 40°N., between Long. 50°W. and 56°W., and also that at the same depth a similar plain is found east of the Ridge in the Northern Canary basin. They are dotted with small sea mounts of variable height whose exact shapes have not yet been determined. The size and number of these appear to increase toward the south, and the southern extremities of the plains consist of smooth horizontal stretches interrupted by pronounced elevations and depressions.

(2) The Mid-Atlantic Ridge is characterized by two strongly contrasting types of topography: (a) The central backbone of the Ridge, or Main Range, which is shoaler than 1600 fathoms, consists of a series of parallel ranges trending NE.–SW. Several of these rise to less than 800 fathoms. Their trend follows roughly that of the Main Range. The portion of the Main Range to which the most attention was devoted is between Lat. 30° and 34°N. In this area its width is of the order of 150 miles, and it is of the order of several hundred miles in the area of the Azores.

(b) The flanks, between the 1600- and 2500-fathom isobaths, consist of a succession of smooth shelves, each from 1 to 50 nautical miles or more in width. This zone is 200–300 miles in width.

(c) The region between the limit of the 2900-fathom plain and the foot of the first of the series of shelves characterizing the flanks of the Ridge, at 2500 fathoms, in some localities stands out as a distinct physiographic province.

(3) The following local features are noteworthy:

(a) Close to 31°N.Lat. a deep east-west trench extends from about 41° to 43°W.Long. and cuts deep into the Main Range. Its deepest point is at 2800 fathoms. Crushed and metamorphosed ultrabasics were brought to the surface by dredging its flanks.

(b) At 30°15′W., 34°N., a flat-topped sea mount rises to 180 fathoms, about 100 miles southeast of the Main Range. The dredge brought up calcareous discs of probably Cenozoic age off its top. They were about 15 cm in diameter and about 4 cm thick.

(c) Another sea mount was found at 33°43′N., 62°30′W., 150 miles NE. of Bermuda, shoaling to 780 fathoms, having a NW.-SE. elongation, an unknown total length, and a width of 4 miles across its flat top.

(d) Another flat suboceanic plain occupies the bottom of the basin separating Bermuda from the Northeastern United States, at a depth of 2650 fathoms.

Introduction

The authors' intention is to bring as rapidly as possible to the public's attention the existence of certain very important features of ocean-bottom topography. It is hoped that they will attract the attention of investigators to certain crucial points which can to a large extent be elucidated by a more widespread use of recording fathometers with a range of 0 to 4000 fathoms.

The present paper is the first of a series which will describe the data obtained by the Atlantis cruises in the North Atlantic since the summer of 1947. It was judged sufficient to illustrate it by means of maps and fathograms. Of course, the latter provide only somewhat distorted profiles of the sea floor. However, this distortion is always small enough so that all the striking features stand out very satisfactorily. Part II of this paper will give a series of corrected profile drawings.

Since the 1947 summer cruise (cruise #150) the Atlantis has made three cruises across the North Atlantic (cruises 151, 152, 153). Also, three almost uninterrupted fathograms of other ships crossing the Atlantic, as well as several shorter ones and numerous discrete sounding lines, were made available for examination, thanks to the kindness and co-operation of the officers of the U. S. Navy Hydrographic Office. Some of the main features of these data will be mentioned here in passing. Their detailed presentation is reserved for a later paper.

Acknowledgments

This work was made possible through the support of the National Geographic Society, The Woods Hole Oceanographic Institution, The Geological Society of America, and the Bureau of Ships, Navy Department. Most of the data were obtained by the Research Vessel Atlantis, belonging to the Woods Hole Oceanographic Institution. The authors are very grateful to Dr. Columbus O.'D. Iselin for facilitating in many ways the task of obtaining data from cruises other than those with which the authors were directly connected. The authors are also much indebted to Dr. J. B. Hersey for the loan of his data obtained on Atlantis cruises prior to cruise 150. Through the courtesy and co-operation of the U. S. Navy Hydrographic Office many additional data have been made available to the authors. It is expected that in co-operation with this institution the authors will soon obtain a much more complete and satisfactory picture of the North Atlantic Ocean bottom. Finally the co-operation and work of Adrian Lane, Master of the Atlantis, and of his crew were greatly appreciated at all stages of the field work.

The Mid-Atlantic Ridge: Generalities

The Mid-Atlantic Ridge (or Swell, or Rise) has attracted much attention since the end of the nineteenth century. It is the most conspicuous feature of the Atlantic Ocean basin and is essentially a long narrow submarine mountain range which extends from about Lat. 65°N. (Iceland) to Lat. 50°S. It parallels the American, European, and African coasts (Pl. 1). At the equator this parallelism is strikingly illustrated by a pronounced E.-W. flexure.

Plate 1 shows the axis of the Ridge to be al-

most entirely above 2240 fathoms (4000 m), and bordered by deeper regions which are themselves split up into a series of basins, whose depths are of the order of 3000 fathoms, by ridges branching out from the main body of the Mid-Atlantic Ridge. These diverging mountain ridges give a herringbone-like aspect to the relief of the Atlantic floor, particularly in the southern hemisphere. The high parts of the Ridge shoal to less than 1000 fathoms in places, and the highest peaks form groups of islands such as the Azores and St. Paul's Rocks. North of Lat. 45°N. the Mid-Atlantic Ridge broadens and rises gradually to Iceland. South of Lat. 50°S. the Ridge bends eastward, parallel to the South African coast, and is believed by some authors (Wiseman and Seymour Sewell, 1937) to extend to the Carlsberg Ridge in the Indian Ocean.

Previous Hydrographic Work

The map shown in Plate 1 was published in the account of the Meteor oceanographic expedition of 1925–1927 (Maurer and Stocks, 1933), during which 14 echo-sounding profiles, with soundings spaced every 20 minutes of time, were run from coast to coast between Lat. 20°N. and 50°S. The Meteor (Dietrich, 1939) and Altair (Wüst, 1939) did more surveying in the North Atlantic in 1934–1939, on the ridge north of the Azores and on the Azores plateau itself. The U.S.S. Muir made two crossings of the Atlantic: from Philadelphia to Dakar and back in 1945, taking soundings every half hour.

All these soundings have contributed greatly to our knowledge of the bathymetry of the Atlantic Ocean basin and have in particular helped to emphasize the distribution of submarine mountain ranges with respect to the deeper basins. However, these surveys consisted of a series of discrete soundings. Until now no continuous fathograms of any portion of the Mid-Atlantic Ridge have been available. As will be shown, important features of ocean-bottom structure may escape notice if continuous fathograms are not available.

Gravity Measurements

Vening-Meinesz (1934) has shown that the Mid-Atlantic Ridge does not seem to be associated with any conspicuous gravity anomalies. However, the isostatic anomalies tend to be positive, particularly in the area of the Azores, where the regional isostatic anomalies are the smallest, showing that the compensation of the Azores plateau, like that of many other island blocks, is regional.

Seismicity

Though this is one of the principal seismic belts of our globe, its activity is in no way comparable with that of the Circum-Pacific Belt. All the shocks known to have originated in the area of the Mid-Atlantic Ridge are of the shallow type and are mostly of the c and d classes (Gutenberg and Richter, 1949). There seem to be three regions on the Ridge in which seismic activity is concentrated: the eastern extremity of the equatorial flexure, in the vicinity of St. Paul's Rocks; the western extremity of the flexure, around 10°N. 40°W.; and in the vicinity of the Azores. The portion of the Ridge between Lat. 25° and 35°N. also seems to be somewhat more active than the rest of the Ridge, though this may be due to the favorable location of these epicenters with respect to the existing seismological stations. The first three localities mentioned have produced much larger shocks than have been noted elsewhere on the Ridge—class b and even a (Azores, Nov. 25, 1941). The Mid-Atlantic Ridge is thus the locus of a certain amount of unreleased stress, which seems to be mostly concentrated at the two ends of the equatorial flexure and also in the vicinity of the Azores plateau.

Theories on the Origin of the Ridge

There has been much speculation as to the origin of the Mid-Atlantic Ridge. Haug (1900) believed it to be the median anticline of what he called the Mid-Atlantic "geosyncline".

Taylor (1910) considered it as a horst. Wegener (1924) believed it to be the bottom of the rift that was opened up prior to the separation and drifting apart of the bordering continents. Molengraaff (1928) was of essentially the same opinion. H. S. Washington (1930) stresses the geological significance of the ultrabasics of St. Paul's Rocks. These rocks are peridotites that indicate crushing and meta-

morphism by pressure. He regards them as evidence of lateral pressure in the building of the Ridge. He also remarks that Prinz's theory of differential torsion of the two hemispheres might explain the prevalent trends of the Ridge, and in particular the equatorial flexure.

Bucher (1940) believes in the essential similarity of the pattern of continental and oceanic structures in the North Atlantic and surroundings areas. He says the pattern of the ocean floor seems to be "comparable to that of the basins and swells of the continental areas outside the orogenic belts, although the scale is both larger horizontally and vertically on the oceanic surfaces."

Umbgrove (1947) emphasizes the symmetry of the distribution of basins and ridges in the South Atlantic and in the African continent and suggests that the prevalent trends are here undoubtedly those of the two major linear patterns of the earth's crust (the N.–S., E.–W., and bisecting systems). Hans Cloos (1939) on the basis of an experiment on clay has shown that the type of topography characterizing the Azores plateau can be explained in terms of doming of a section of the earth's crust with formation of fractures parallel to the longest dimension of the domed section (NW.–SE.). Subsequent extrusion of magma through fissures would have formed the NW.–SE. ridges surveyed by the ALTAIR.

Agostinho (1936) also believes the major topographic features of the Azores plateau are due to the extrusion of volcanics through predominantly northwest-southeast fractures. In addition he thinks the origin of this big bulge in the Ridge is somehow related to the fact that it is situated at what he considers the intersection of two major submarine trends: the almost north-south trend of the Mid-Atlantic Ridge and the almost east-west trend formed by the succession of banks beginning with the Great Banks, through Milne Bank, the Azores, and the banks west of Gibraltar.

Thus the status of the problem of the origin of the Mid-Atlantic Ridge is somewhat confused. The present authors are not prepared to take any definite stand on this aspect of the problem. However, the possible implications of the results obtained so far are indicated, since our investigation has revealed a series of hitherto unsuspected features of the ocean floor, both on the Mid-Atlantic Ridge itself and in other parts of the North Atlantic.

ACCURACY OF DEPTHS AND POSITION

Contours of the ocean bottom were drawn where such a procedure was judged practicable —*i.e.*, when intersections between various parts of the ship's track occurred, or when the distance between two tracks was sufficiently small. No absolute criteria for the justification of such a procedure can be established, since the determining factors, such as the type of topography and accuracy of navigation, are subject to considerable variations from place to place and from day to day. Accuracy of the topographic maps varied and depended upon numerous factors, the relative importance of which cannot always be determined. The following causes of error should be noted, and kept in mind when considering the results here reproduced.

(1) The ship's position was obtained by astronomical methods and dead reckoning. An accuracy of ±1 mile is a reasonable estimate for the ship's position as obtained in the evening and morning from star fixes, since especial care was taken. The noon fix should not be relied upon to better than ±2 miles. The largest possible errors would occur for intermediate times.

The effect of currents and wind on a small ship, cruising at 8 knots, can be very great and had to be considered several times in the drafting of the hydrographic maps. Such corrections are made possible by the closing, at one or several points, of the network of ships' tracks. Accuracy is proportional to the number of ships' tracks available, particularly when associated with star fixes. Such corrections were made by mutual adjustment of the ship's supposed courses drawn on tracing paper, which process was continued until all intersections were made consistent with the soundings. In many cases the necessary adjustments were small, and in several cases unnecessary. Several times when some interesting feature was encountered, such as an unusually high ridge, box surveys were conducted. A zigzagging course was adopted, each change in course being determined from the readings on the fathogram, in order to try to enclose the feature within a network of

shortest possible tracks. Accuracy of positioning of the soundings increases with the number of intersecting courses and with more rugged topography. However, absolute geographical positioning will remain open to errors of a larger order of magnitude, except when there are one or several star fixes in the area. These are always fixed points in the transformations of the adjustment.

(2) The errors of sounding may be due to three causes:

(a) Departure from 60 cycles of the frequency of the generator supply to the synchronous motor running the stylus arm of the recording apparatus. The vertical divisions of the recording tape are calibrated to give exact depth readings for a veolocity of the stylus arm corresponding to 60 cycles. A departure from this figure of ± 1 cycle will give a reading which will be in error by $\pm\frac{1}{60}$ of the true depth, which at a depth of 2000 fathoms would mean an absolute error of 33 fathoms. Most of the recording is free from errors of ± 1 cycle or more—or, at least, these will usually be readily detectable on the fathogram. However, since there was no automatic frequency-control device, changes of the order of half a cycle may have been fairly common and may have been overlooked. Therefore, in oceanic depths the soundings should not be relied upon to better than ± 20 fathoms.

(b) The angle at the apex of the outgoing cone of sound, which leads sometimes to the so-called slope correction (Adams, 1942). This error is not sufficiently large to be taken into account in the plotting of the maps. Thus if a vertical wall were supposed to rise from the ocean floor to sufficient height from a depth of 2000 fathoms, and if we suppose the half angle at the apex of our cone of sound to be of the order of 25°, the error in the positioning of the foot of the slope would be of 12000 sin 25° = 5000 feet approximately. If this wall were 1000 fathoms high, it would therefore record as a slope of $\tan^{-1}\frac{6}{5}$ or 50° approximately. Now since 5000 feet is always an error of lesser magnitude than those involved in dead-reckoning navigation, and since the steepest continuous average slopes of any length that were recorded were of the order of 25°–30°, there is little reason for applying this correction to the drafting of our topographic maps. We must just keep in mind that the slopes shown on the fathograms are a little less steep than the true slopes, and that vertical cliffs such as might be expected to occur in connection with long continuous rises of many thousands of feet over a few miles will not show up as such on fathograms.

(c) Variations in the velocity stratification of the ocean. The errors due to this cause are not very large (of the order of 1 per cent of the total depth or less). We here follow the general policy of such centers of hydrographic study as the U. S. Hydrographic Office and the U. S. Coast and Geodetic Survey and disregard them.

General Description of the Areas Investigated

Plate 2 shows the various sounding lines now available. They include Atlantis cruises Nos. 143, 144, 147, 150, 151, 152, and 153, and most of the lines made available to us through the courtesy of the U. S. Navy Hydrographic Office. Since new data are coming in continuously, it was deemed inadvisable to make a detailed presentation of the material examined so far. Therefore, except for a few detailed local surveys, we will limit ourselves to a very generalized description of the various types of submarine topography in the North Atlantic.

Plate 2 was drawn to illustrate (1) the general trend of the Ridge between Lat. 40°N. and 29°N.; (2) the distribution of the known conspicuous sea mounts; (3) the extent of the data upon which we have determined the generality of certain types of submarine topography; (4) the control upon which to a large extent our 1600-fathom contour was based. Where no lines are shown, we either omitted this contour or used the few scattered soundings available on the H. O. 0955 and 0956 charts.

The fathograms shown in Plates 3, 4, 5, and 6 were obtained during the Atlantis cruise No. 150 and illustrate the major types of topography in the North Atlantic. We will confine ourselves mostly to a description of the area covered on this cruise.

A study of the lines in Plate 2 has shown that many of the types of topography encountered are characteristic of broad areas of the ocean floor.

On cruise 150 the Atlantis went from Woods Hole to Bermuda, from Bermuda to the Azores

and back, thus crossing the northwestern basin of the Atlantic (the "North American Basin") and the Mid-Atlantic Ridge. These areas were characterized by several distinct types of bottom topography. Thus the slightly shoaler part of the North American basin, which was crossed on the trip from Woods Hole to Bermuda, has somewhat different characteristics from those of the deeper part, between Bermuda and the Ridge. The central and deepest part of the latter is occupied by a great horizontal plain at the depth of 2900 fathoms. The areas bordering this basin, on the other hand, were characterized by more rugged topography, and the eastern border was quite different from the western. The rugged and high central part of the Mid-Atlantic Ridge is quite different from its shelved flanks. The reader should realize that this subdivision of the ocean into separate zones is by no means arbitrary, but corresponds to what appear to be distinct physiographic provinces of the ocean bottom.

Ocean Bottom Between Cape Cod and Bermuda

On cruise 150 one continuous fathogram from Woods Hole to Bermuda was obtained. This has since been matched by numerous other fathograms taken by the Atlantis and other ships. Portions of the fathogram of cruise 150 are reproduced in Plate 3. This shows a succession of steplike horizontal or imperceptibly sloping levels at 1500, 1950, 2100, and 2500 fathoms (Pl. 3a). The last three are more pronounced than on a typical crossing of the continental slope. However, a 1500 ± 100 level is a fairly general feature of the continental slope between Lat. 40° and 35°N. The deepest section of ocean floor along this line occurs about half way between Woods Hole and Bermuda, at 2650–2700 fathoms. It is about 250 miles wide and is remarkably flat and featureless, except for one fair-size sea mount at 36°38′N., 67°55′W. Unfortunately this sea mount was encountered on the homeward bound course, when the fathometer was not recording. Subsequent cruises by the Atlantis (151 and 153) and the R/V Caryn (winter of 1947–1948) have shown that it rises to 1590 fathoms.[1] During cruise 150 the Atlantis obtained a core 20 miles southeast of this mount. It showed coarse quartz sand stratifications in the upper section of the core. This sand is now being studied by D. Ericson. Recent (Trask, Phleger, and Stetson, 1947) investigation has shown the presence of sand in the deep basin of the Gulf of Mexico. More recent cruises of the Atlantis have found sand at depths of many feet in various parts of the North American basin. The presence of these sands poses one of the most baffling problems of submarine geology.

At Lat. 34°N. on the track of A150, at the end of the 2700-fathom stretch, the bottom starts a gentle overall rise toward Bermuda. The ocean floor on this slope is quite different from that noted off the continental shelf. The succession of levels is not so apparent as it was on the continental rise. Numerous steep sea mounts (10- to 30-degree slopes, rising between 100 and 500 fathoms above the ocean floor on which they are situated) dot the gentle overall rise (Pl. 3). Only in between these peaks is there any indication of the existence of levels. Thus Plate 3 shows a shelf at 2500 fathoms, before the steeper rise toward Bermuda starts. This shelf is even more pronounced to the east (A151). It is preceded on all available fathograms by a sharp peak.

The Vicinity of Bermuda

Figure 1 shows a bathymetric map of the approaches to Bermuda, on a plotting-sheet scale, and the eight Atlantis tracks upon which these contours are based. The base of the island has a NE.–SW. trend and is about 100 miles wide in a NW.–SE. direction. Approaching Bermuda from the north (Pl. 3d), at the depth of 2450–2500 fathoms the first change in slope occurs in the slow upward grade toward the south. After this the bottom rises much more rapidly. These fathograms show the large sea mount 25 miles north of Bermuda, rising to less than 500 fathoms. The steepest part of the slope is between 850 and 100 fathoms; its average inclination is of the order of 20°–25°.

[1] Recent data show that the whole section of the North American basin northeast of the Atlantis 150 track is characterized by a flat plain at 2650 fathoms, dotted by a number of large flat-topped sea mounts some of which rise to less than 800 fathoms (Pl. 2). A number of these mounts appear to string out in a southeast direction, away from Cape Cod. A detailed report on this area is now in preparation.

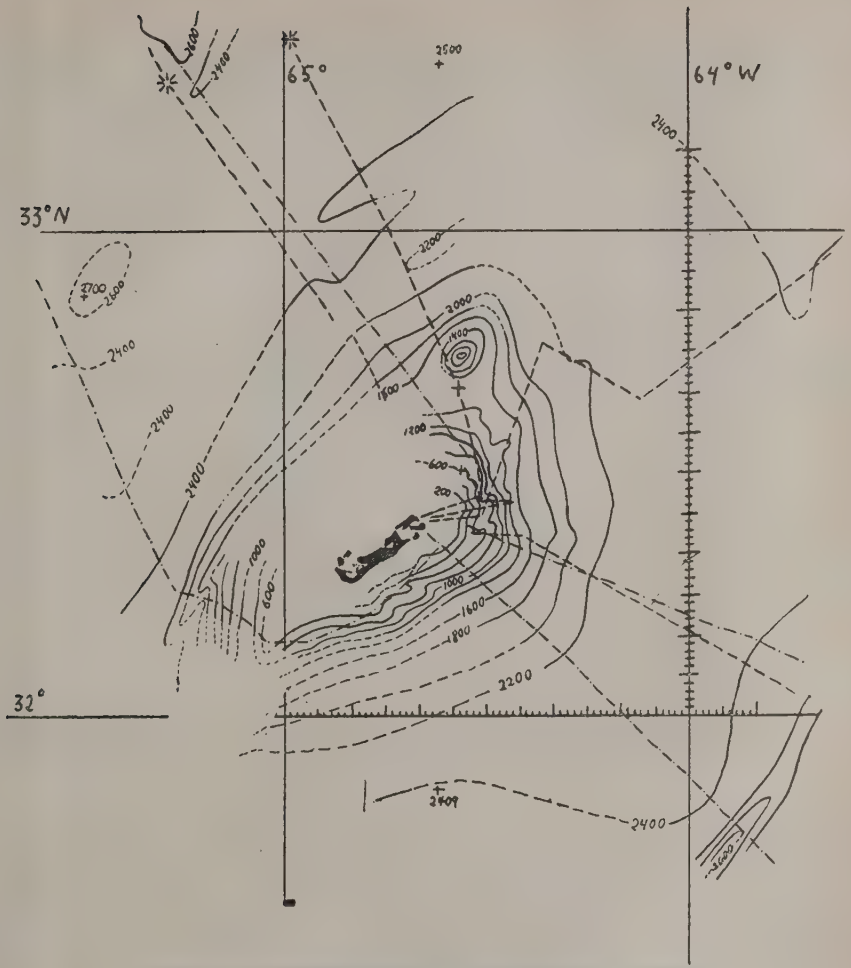


FIGURE 1.—BATHYMETRIC CHART OF THE APPROACHES TO BERMUDA
Contour interval 200 fathoms.

Similarly, as one goes east from Bermuda the bottom drops off very rapidly to 2200 fathoms, and then more slowly to 2500. This seems to be the depth at which, as far as all the north, northeast, east, and southeastern approaches toe Bermuda are concerned, the bottom may be said to start feeling the influence of the island. On the northeastern course from Bermuda the 2500-2550 fathom stretch of sea floor extends for about 32 miles. It is then followed by a rise, gentle at first, then steeper and steeper until the depth of 780 fathoms is reached 130 miles from Bermuda. This sea mount was originally discovered by the U.S.S. MUIR on its cruise from Philadelphia to Dakar in 1945. The writers conducted a box survey here (Fig. 2); this showed that the sea mount has a flat top at about 780 fathoms. It is elongated in a NW.–SE. direction. Its exact length is unknown, but it is probably less than 30 miles.

The fathogram is reproduced in Plate 3d. Its appearance recalls somewhat the description given by Hess (1946) of the Pacific guyots, and the sea mounts of the Gulf of Alaska described by Murray (1945). A short core obtained from the summit shows a discontinuity between a

13-cm layer of Recent sediment and an underlying chalky mud containing Eocene Foraminifera, suggesting that in recent times some scouring agent has been active close to the surface

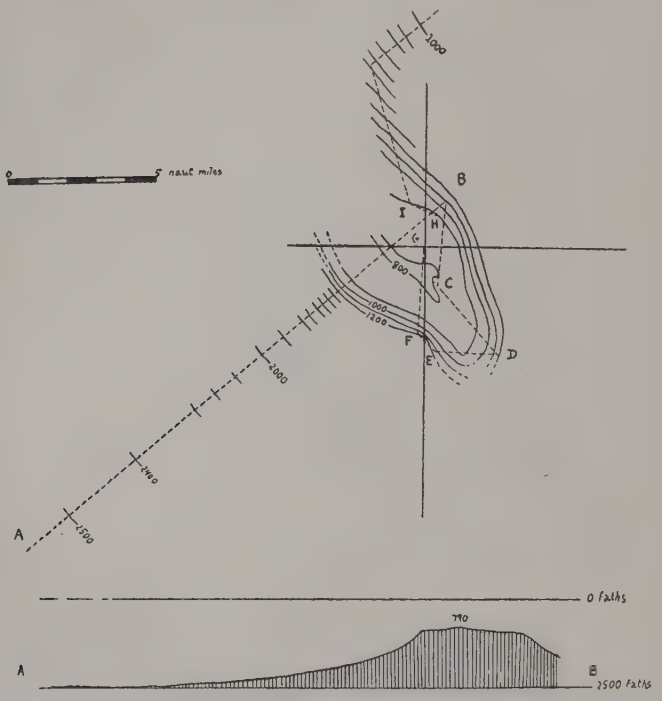


FIGURE 2.—SEA MOUNT NORTHEAST OF BERMUDA

The letters corresponding to changes of course are shown at the corresponding places on Plate 3d. Contour interval 100 fathoms. The vertical and horizontal scales on the profile are the same.

miles wide. Thence a generally level plateau at 2400 fathoms extends for about 60 miles, followed by a steplike succession of flat stretches at 2550–2600 fathoms and 2750–2800 fathoms, of this sea mount. Northeast of this mount, the bottom drops off rapidly to 2700 fathoms.

THE OCEAN FLOOR BETWEEN BERMUDA AND THE 2900-FATHOM PLAIN

The section of ocean floor here considered extends from points A to B of Plate 2 on the northern A150 track.

The fathogram reproduced in Plate 4a shows gentle topography in this section of the ocean floor. After a short (3 miles) 2700-fathom stretch northeast of the sea mount just described, it is characterized essentially by a long gentle swell which rises to 2300 fathoms and is about 60 with perhaps an intermediate flat step at 2650 fathoms having a width of 20 miles (Pl. 4a).

The end of the 2750 level seems to be characterized by a narrow (2 miles) flat-bottomed trough (2840 fathoms) followed by a sharp peak (2350 fathoms) and a broad hump rising to 2560 fathoms and 20 miles wide (Pl. 4a).

To the south the rise from the 2900-fathom plain to Bermuda is more rugged. Thus all soundings pertaining to this area show that there are numerous peaks, separated by deep valleys.

The fathograms obtained between Bermuda and the 2900-fathom plain confirm this. They show that the bottom consists of a succession

of much sharper peaks, separated by deep valleys and narrow flat-bottomed trenches reaching much greater depths than any valley on the northern track (2900 to 3100 fathoms). Judging from existing data, their trend appears to be northeast-southwest.

The 2900-fathom Plain

At point B on the northern route (Pl. 2) a depth of 2900–2880 fathoms is reached. At this point and depth begins what is perhaps the most remarkably flat stretch of ocean floor in the Atlantic. It extends, with a few knolls here and there, for over 300 miles of track (B to C on Pl. 2).

A typical fathogram obtained in this area is reproduced in Plate 4b. Both the western (Pl. 4b) and the eastern extremities (Pl. 4c) of this plain are characterized by a multiplication of the otherwise small number of knolls. These look like small pimples interrupting the otherwise horizontal ocean floor. This 2900-fathom plain is now known to occupy a very large section of the North American basin. Though we cannot yet delineate its boundaries precisely, owing to the insufficient amount of continuous fathograms, it may extend as far north as Lat. 40°N. In these latitudes it might be 50 or 100 fathoms shoaler. Several fathograms show it to be several hundred miles wide in the vicinity of Lat. 31°N., though it appears to be marked by more numerous and higher knolls. Many of these rise to over 100 fathoms above the level plain. Also several higher peaks rise 1000 fathoms or more above this level. Some of these appear to be ridges having either due north or east-northeast trends. The level plain is somewhat deeper (2950 to 3000 fathoms). Its beginning, at 31°N., 58°W. on the fathograms of A151 is characterized by a high peak (about 1000 fathoms in height), having slopes of the order of 20° to 30° on the fathogram. (The width of its base is about 9 miles.) In other words, when the slope correction is considered, its walls would perhaps be more than 40° steep (Fig. 3). It is preceded by a small trough, 2–3 miles wide, the bottom of which is horizontal at 3100 fathoms.

The fathograms of Atlantis cruise 151 show a similar plain occupying the floor of the basin east of the Ridge, between the Ridge and the northwestern coast of Africa (the northern Canary basin). It appears therefore that this 2900-fathom plain is of great regional significance. Its aspect on the fathograms suggests that vast portions of the ocean floor have remained tectonically undisturbed since their formation. The

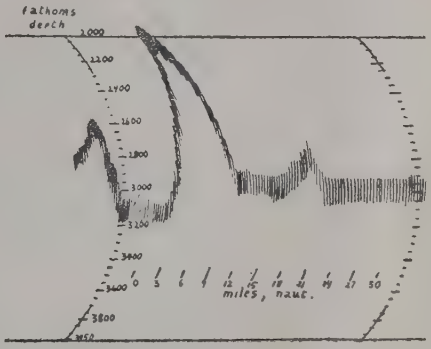


Figure 3.—Sea Mount at the Western Edge of the 2900-Fathom Plain at Lat. 31°N.

This is a tracing of a fathogram showing a sea mount located at the point marked X on Plate 2. (31°N., 58°W., approximately).

small knolls may be due to one of several causes: block faulting, lava escaping through fissures, or submarine volcanoes. Their true shapes and distribution pattern over the ocean floor remain to be ascertained.

The Ocean Floor between the Eastern Edge of the 2900-fathom Plain and the Foot of the 2500-fathom Terrace

The 2900-fathom plain ends rather aburptly at point E on Plate 2 against a series of high peaks, one or two of which have slopes exceeding 30°, and heights of as much as 500 fathoms (Pl. 4c). All available fathograms between Lat. 36° and 30°N. show the presence of this mountainous region between the 2900–3000 fathom plain and the "Terraced Zone" of the Ridge. Seismic work by Ewing and Press aboard the Atlantis on cruise 150 has shown that this area gives a different type of reflection, indicating the presence of sizable amounts of mud (several hundred feet), as against practically none on the 2900-fathom plain and much larger quantities in the Terraced Zone of the Ridge.

A sea mount of exceptional dimensions is located at 35°12′N., 45°33′W. Its western foot is marked by a small trough (2600 fathoms). It rises from this depth to 1300 fathoms (Pl. 4d). It marks the end of the mountainous area and the beginning of the Terraced Zone of the Ridge.

The Terraced Zone

On the eastern side of the peak we have just described the bottom drops off to 2500 fathoms, at which depth it remains approximately flat for about 35 miles (Pl. 4d). On the track of Atlantis 150, along Lat. 31°N., a 2500-fathom level stretch of the same width was found, preceded also by a high peak at approximately 31°N., 45°30′W. shoaling to 1800 fathoms. One cannot say what relation these two remarkably similar structures bear to one another.

This marks the beginning of the succession of flat stretches characterizing the lower flanks of the Ridge, which, for lack of a better term, we shall call terraces. The area characterized by this type of topography we shall henceforth call the Terraced Zone. The authors do not wish to imply anything concerning the origin of these flat stretches by the use of the name "terrace." It was merely deemed more advisable to use some familiar term instead of coining a new name.

Along the Atlantis 150 track the 2500-fathom terrace ends against a 2000-fathom peak bordering a 2300–2350-fathom terrace, approximately 35 miles wide (Pl. 4d). The inner eastern edge of this terrace is marked by a broad hump of small elevation, itself broken up into a series of narrow ridges shoaling to 2100 fathoms. Next comes a 2250–2270-fathom terrace 25 miles wide and characterized by its remarkable flatness. Similar terraces appear on all fathograms approaching the Ridge between Lat. 35° and 30°N. at approximately the same depths. Conceivably the differences in depth for terraces found along parallel lines would not always be real, but would be due in part to instrumental causes.

The 2250-fathom terrace marks the beginning of that portion of the Ridge and its flanks which was closely investigated during the summer of 1947. The zone between the 2250 and 1600 isobaths is 60–100 miles wide on both sides of the Ridge. It is characterized by a discrete series of flat terraces that occur at the same depths on both sides of the Ridge, at points hundreds of miles apart. The reflection shooting studies done during the same cruise by Ewing and Press indicate great thicknesses of sediments on these terraces (up to 1000 feet and more). The fathograms reveal that the most conspicuous terraces, remarkable both in numbers, in different localities, and in total length, are at depths of 2250, 2150, 2100, 2050, 1950, 1850, 1800, 1750, 1700, and 1600 fathoms. Of these the most numerous were at 2250, 2050, 1950, 1850, and 1800 fathoms. Plate 5 reproduces a few typical records from the terraced zone. We have given no detailed charts of the exact distribution of all the individual terraces enumerated above because the number of tracks available over most of the terraced zone is insufficient as yet to enable us to establish any definite correlations between most of them. However, in a few cases it has been possible to establish without much doubt the continuity of some of these terraces over great distances.

In Plate 7 the 1900-fathom terrace might be continuous for more than 90 miles and appears to follow closely the general NE.–SW. trend of the Ridge. The 2050-fathom terrace might be continuous for about 80 miles. The corresponding fathograms are reproduced in Plate 5a. The fathograms of the crossing of the Atlantis 153 cruise over this area show that the 2100-fathom level (Pl. 7) extends for perhaps another 100 miles farther west. Possibly, therefore, these terraces form a series of horizontal fringes contouring the outer edge of the higher portions of the Mid-Atlantic Ridge.

Plate 5b shows the fathogram obtained in the region of point D on Plate 2. The summit of the peak on the extreme right corresponds to the change in course made at that point, indicating that the change occurred before reaching the true summit of the sea mount. It emphasizes the possibility of a correlation between the 1700-, 1750-, and 1850-fathom terraces on each side of the sea mount. The portions of these visible on the fathogram would be sections of what may well be a continuous series of terraces circling the flanks of the sea mount.

Many of the terraces described are horizontal, but in some there is evidence of tilting. This is particularly well illustrated by the fathogram

shown in Plate 5c in which a break is suggested in the center of a 1750-fathom terrace with subsequent tilting of the left (southwestern) portion. Many of these terraces are bordered on their outer edge by peaks from 50 to several hundred fathoms in height. Others are enclosed on both sides by steep walls having slopes of as much as 30° to 35°. Examination of the fathograms obtained by the ATLANTIS cruise 151 reveals that the same terraces, at exactly the same depths and characterized by the same horizontality over many miles, are to be found between 1600 and 2500 fathoms off the coast of North West Africa. Plate 5d shows the aspect of the terraced zone immediately south of the area represented by Plate 7.

THE MAIN RANGE OF THE MID-ATLANTIC RIDGE

This part of the Ridge is notable for the absence of terracing. It consists essentially of a series of parallel ridges trending NE.–SW., and shoaling in places to less than 800 fathoms. Plates 6a and b show a few samples of the records obtained over the Main Range.

Only at the outward edge of the Main Range is any evidence of terracing found; it is in the form of flat-bottomed valleys (Pl. 6a, b; Pl. 5a) that appear mostly in the transition zone between the Main Range and the Terraced Zone The depths of their level floors are those of the shoaler series of terraces recognized elsewhere in the terraced zone: 1600, 1700, 1750, 1800, and 1850 fathoms.

Wherever box surveys were conducted over the Main Range or where the intersection of two of the ship's courses made the drawing of isobaths possible, the ridges show a remarkably constant NE.–SW. trend. This is also the trend of the Main Range as a whole in the area surveyed, as may be seen from Plate 2. Plate 7 emphasizes the NE.–SW. trends of the individual ridges of the Main Range.

Dredging the eastern flank of the steep ridge running along the northwest edge of the 2100-fathom terrace at point G of Plate 7 brought up a large block of manganese-encrusted limestone of probably Cenozoic age.

A major exception to the NE.–SW. trends of this area is a deep trough running E.–W. along Lat. 30°N. from 41°W. to 43°W., which can be seen in the southwestern section of Plate 7. A detailed survey was performed in this area (Pl. 8; Pl. 6c, d). The trough is bounded by steep walls having in places average slopes of the order of 30°. The deepest point of the trough is at 2800 fathoms in the western part. The bottom appears to be irregular; two deeper sections (more than 2600 fathoms) are separated by a narrow pass at 2200 fathoms. Several dredging stations were made here, on both the northern and southern flanks of the trough, in the general area of the end points of the tracks. In each case numerous rocks were brought to the surface. Shand (1949) identified them as being strongly or partly metamorphosed ultrabasics: peridotites, olivine gabbro, and olivine basalt. Many of them show evidence of crushing and slickensiding. One or two specimens are practically fault breccia. Some of the basalt fragments show a glassy surface, indicating rapid chilling. Both the topography of this trough and the nature of the rocks obtained therefrom suggest that it may be a graben. It seems significant that this feature is in the center of one of the seismically more active regions of the Mid-Atlantic Ridge (between Lat. 25°N. and 35°N.). This and the absence of traces of the terraced type of topography along the walls of this trough would indicate that it is a fairly recent feature, superimposed upon the typical Mid-Atlantic Ridge type of topography.

Finally we call attention to the remarkably large sea mount at point E on Plate 2. (*See also* Figure 4 and Plate 6c, left end.) Here is another sea mount of the flat-topped variety, which rises to less than 200 fathoms from the surrounding bottom at 1900 fathoms. Dredging the top yielded a large number of calcareous discs characterized by peculiar cavities in their centers. Whereas the outside of the pebbles is relatively smooth, the interior of these cavities is rough. Their dimensions are variable; they average about 15 cm long and about 4 cm thick. Thin sections of these discs reveal the presence of numerous pteropods. According to D. Ericson, all are species that could have inhabited the ocean from the early Tertiary to the present. None are sufficiently characteristic of a specific period to date this limestone.

The fathograms taken in the vicinity of the

Azores show that the plateau on which these islands are situated is limited on its southwest side by a steep slope about 600 fathoms high (Pl. 6c). The topographic map which resulted from the investigations of the ALTAIR shows that the Azores plateau is limited on its sides by such a slope and forms an easterly bulge of the Mid-Atlantic Ridge.

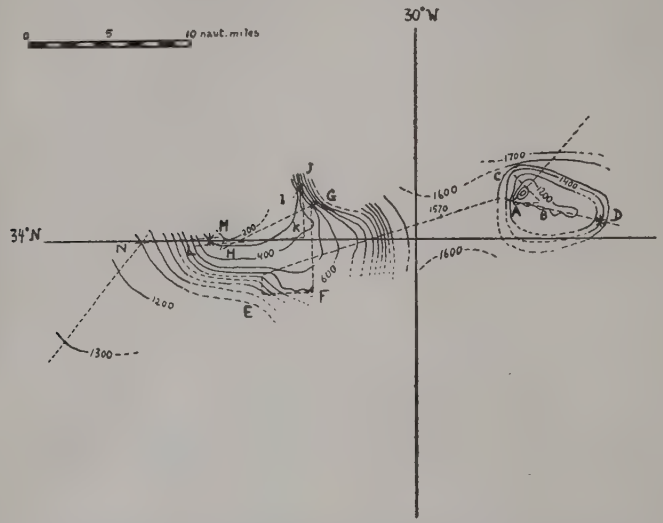


FIGURE 4.—SEA MOUNT AT POINT E OF PLATE 2

This is a sketch-map interpretation of the fathograms shown in Plate 6c of the flat-topped sea mount southwest of the Azores. The letters correspond to those of Plate 6c. Contour interval 100 fathoms.

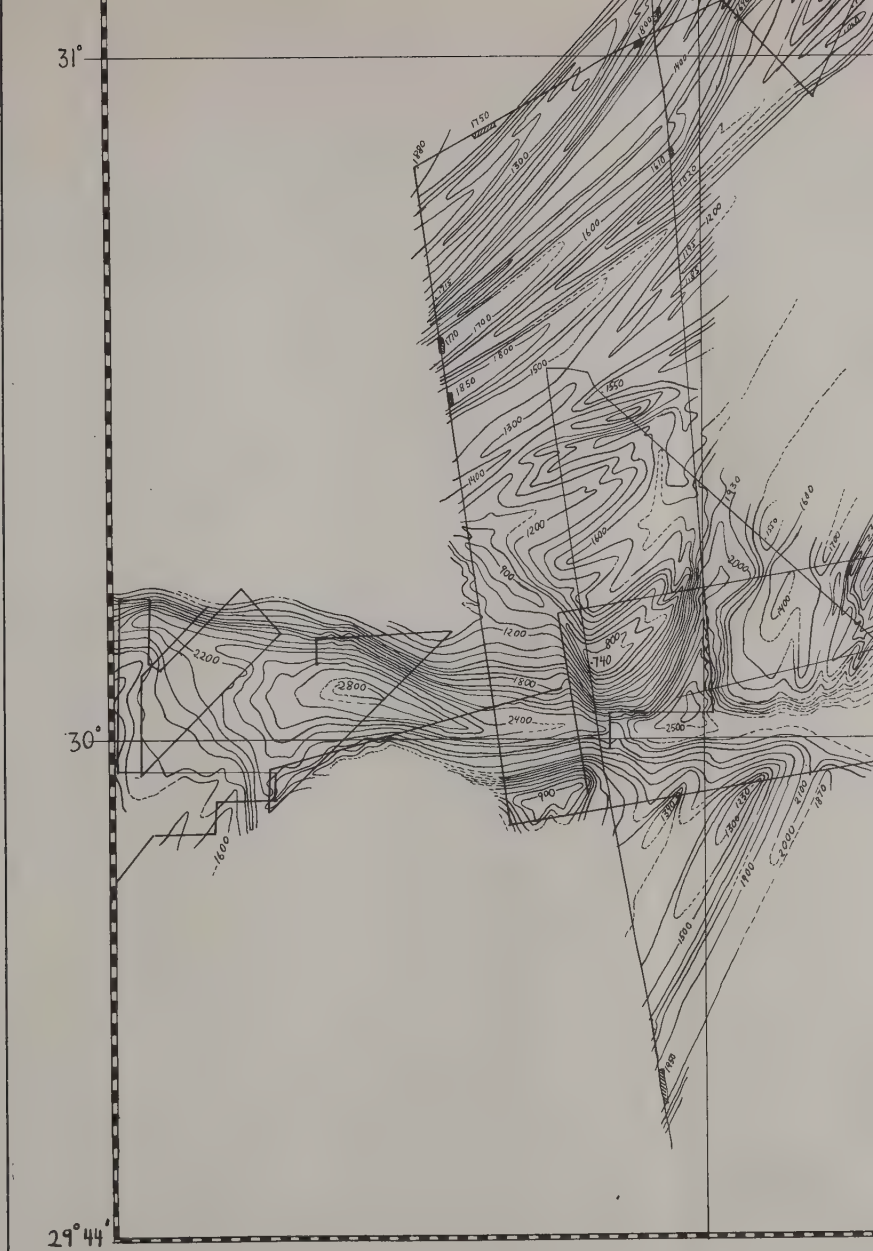
The type of topography shown on the fathograms on the Azores plateau obtained by the ATLANTIS was quite different from any noted on the rest of the Ridge. The surface of the plateau is characterized by a series of ridges, which the ALTAIR expedition plotted as trending NW.–SE. (*i.e.*, approximately at right angles to the trends noted in the Main Range farther south), and whose spacing is entirely different from that of the ridges forming the Main Range of the Mid-Atlantic Ridge. Instead of being close together with only a narrow steep-walled valley separating each two ridges, the ridges on the Azores plateau are separated by broad valleys. It seems improbable that two such different types of structure could have been built by the same process.

SEISMIC EVIDENCE

Reflection-shooting studies of the ocean bottom by Ewing and Press on board the ATLANTIS during the summer of 1947 indicate a greater thickness of sediment in the terraced zone than on the 2900-fathom plain west of the Ridge or on the Main Range. The latter seems to be devoid of any sediment covering the mountain slopes. Each time a mountain was approached, the sediment covering the terraces thinned conspicuously.

INADEQUACY OF DATA OBTAINED BY SOUNDINGS WITHOUT CONTINUOUS FATHOGRAMS

Until now the horizontal plains which, judging by the results of the most recent data, seem to be characteristic of the deeper section of the floor of the North Atlantic Ocean, had gone unnoticed. These sections of the ocean floor were known to be more or less horizontal, without any conspicuous sea mounts. But their unusual flatness, interrupted here and there by a few knolls, which makes them so remarkable,



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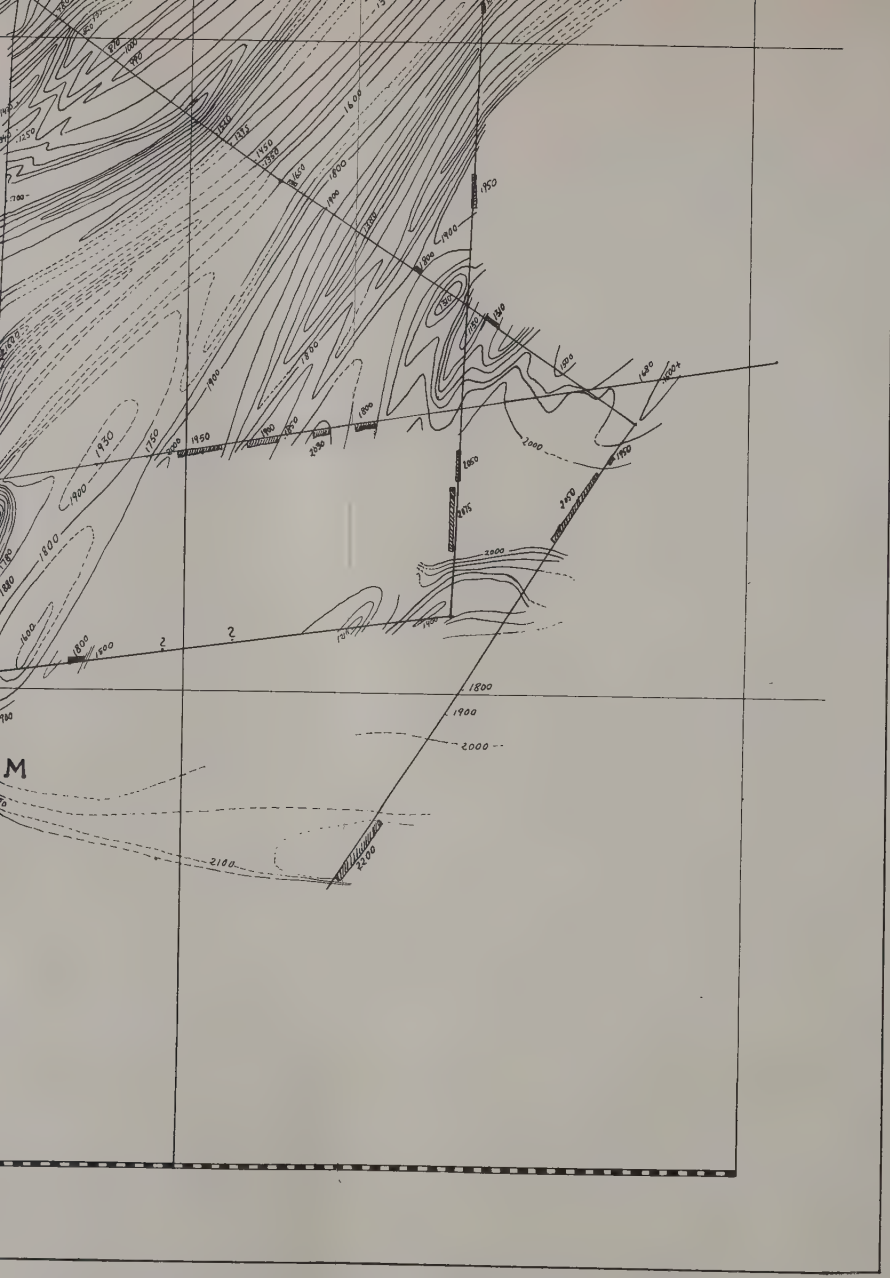


D ON THE RIDGE BY THE ATLANTIS

dicate terraces

fathoms

had escaped the notice of all previous observers. Until quite recently continuously recording fathometers had not been used in the deep ocean. All soundings pertaining to this and other parts of the ocean were made by a visual dial arrangement, and the result was a series of discrete soundings several miles apart; each sounding was probably accurate only to within ± 30 to 50 fathoms. The profile of the ocean bottom obtained from these was like an interpolated curve, with a possible cumulative error between two successive soundings of the order of 50 to 100 fathoms. It is therefore not surprising that these flat stretches of ocean floor, great portions of which are horizontal within the limits of detection by the human eye on a fathometer recording—*i.e.*, to within ±5 fathoms—, remained unsuspected for so long. With the ever more extensive use of continuously recording fathometers, such flat plains are being discovered in the Pacific Ocean also. The late H. W. Murray of the U. S. Coast and Geodetic Survey had given us the following verbal communication:

"In the Gulf of Alaska there is a flat plain lying 140 miles offshore from Yaquina head. It has a length of 200 miles in a northwest-southwest direction and lies at a depth of 1461 fathoms at its northwest end and at 1668 fathoms at its southeast end. It seems to slope or tilt toward the continental slope, where it lies in water 200 fathoms deeper."

Conclusions

The Mid-Atlantic Ridge is characterized by two very distinct types of topography:

(1) The Terraced Zone, a succession of horizontal flat stretches occurring at depths ranging from 2500 fathoms to 1600 fathoms, is found along both flanks of the Ridge, at the same depths. From the few locations that could be correlated, it appears probable that they form fringes along the foot of the Main Range. They are covered by thick sediments. These terraces, at the same depths, recur off the coast of northwest Africa. In a few cases they exhibit evidence of tilting.

(2) The Main Range of the Mid-Atlantic Ridge, above 1600 fathoms, is a succession of parallel mountain ridges, trending NE.–SW. There are no terraces in this section of the Ridge, although the higher terraces are found in valleys, the floors of which are below 1600 fathoms.

Of all the hypotheses on the origin of sections of the Mid-Atlantic Ridge perhaps the least speculative are those proposed by Hans Cloos and J. Agostinho for the origin of the type of topography on the Azores plateau. Though these hypotheses appear reasonable enough for the specific case of the Azores, it does not appear to us to apply necessarily to the rest of the Ridge, for, as we have already noted, the Azores plateau appears to be a feature distinct from the rest of the Ridge, characterized by its own particular type of submarine topography.

Apart from a few highly interesting but scanty geological facts, the evidence about the nature of the Ridge obtained thus far by us is mostly topographic, and even this leaves much to be desired. We therefore cannot conclude much about the origin of the Mid-Atlantic Ridge.

One of the big surprises of the 1947 Atlantis expedition (cruise 150) was the proof of the existence of consolidated Cenozoic limestone on the Mid-Atlantic Ridge. Possibly considerable areas of the Ridge consist of sedimentary rocks. If so, the hypothesis of folded ranges in certain parts of the Ridge should not be rejected arbitrarily, on the sole basis that it is difficult in the light of our scanty knowledge of the history of the earth's crust to explain the why and how of such a process. It must be disproved by experimental and observational data; until then it remains a possibility.

Obviously many more data in the form of hydrographic surveys and fathograms are needed. An accurate bathymetric chart of the Atlantic Ocean would contribute greatly to our knowledge of the structural history of the Earth. Such a chart would also be useful for navigational purposes, since the Atlantic sea floor is marked by numerous features which would provide excellent "landmarks".

Such a project would be greatly facilitated by a more extensive use of continuously recording fathometers. Formation surveying—*i.e.*, surveying by means of a flotilla of ships keeping radar formation and equipped with

continuously recording fathometers—would enable this work to be carried out speedily and efficiently.

References Cited

Adams, K. T. (1942) *Hydrographic manual*, U. S. Dept. Comm., Coast Geod. Survey, Spec. Pub. no. 140.

Agostinho, J. (1936) *Volcanoes of the Azores*, Bull. Volcanologique, Organe l'Assoc. Volcanologie de l'Un. Geodes. Geophys. Inter., p. 123–138.

Bucher, W. H. (1940) *Submarine valleys and related geological problems of the North Atlantic*, Geol. Soc. Am., Bull., vol. 51, p. 489–512.

Cloos, H. (1939) *Hebung-Spaltung-Vulcanismus*, Geol. Rundschau, vol. 30, Zwischenheft 4A, p. 506–510.

Dietrich, G. (1939) *Einige morphologische Ergebnisse des Meteor, fahrt Januar bis Mai 1938*, Ber zweite Teilfahrt Meteor, p. 20–23.

Gutenberg, B., and Richter, C. F. (1949) *Seismicity of the Earth*, Princeton Univ. Press.

Haug, E. (1900) *Les geosynclinaux et les aires continentales*, Soc. Géol. France, 3e ser., Bull. 28.

Hess, H. H. (1946) *Drowned ancient islands of the Pacific basin*, Am. Jour. Sci., vol. 244, p. 772–791.

Maurer, M. and Stocks, Th. (1933) *Die Echolotungen des . . . Meteor . . .*, Wiss. Ergebn. Deutsch Atlant. Esped. . . . Meteor . . . , 1925–1927, Bd. II, Beil. 4–32.

Molengraaff, G. A. F. (1928) *Theory of Continental Drift* (Symposium), Am. Assoc. Petrol. Geol., p. 91.

Murray, H. W. (1945) *Profiles of the Aleutian trench*, Geol. Soc. Am., Bull., vol. 56, p. 757–782.

Shand, S. J. (1949) *Rocks of the Mid-Atlantic Ridge*, Jour. Geol., vol. 57, p. 89–92.

Taylor, F. B. (1910) *Bearing of the Tertiary mountain belt on the origin of the earth's plan*, Geol. Soc. Am., Bull., vol. 21, p. 179–226.

Trask, P. D., Phleger, F. B., and Stetson, H. C. (1947) *Recent changes in sedimentation in the Gulf of Mexico*, Science, vol. 106, p. 460–461.

Umbgrove, J. H. F. (1947) *The pulse of the Earth*, The Hague.

Vening Meinesz, H. F. (1934) *Gravity expeditions at sea*, vol. 2, Delft.

Washington, H. S. (1930) *The origin of the Mid-Atlantic Ridge*, Md. Acad. Sci., Jour., vol. 1, p. 20–29.

Wegener, A. (1924) *The origin of continents and oceans*, Translated from the third German editions of 1922 by J. G. A. Skerl.

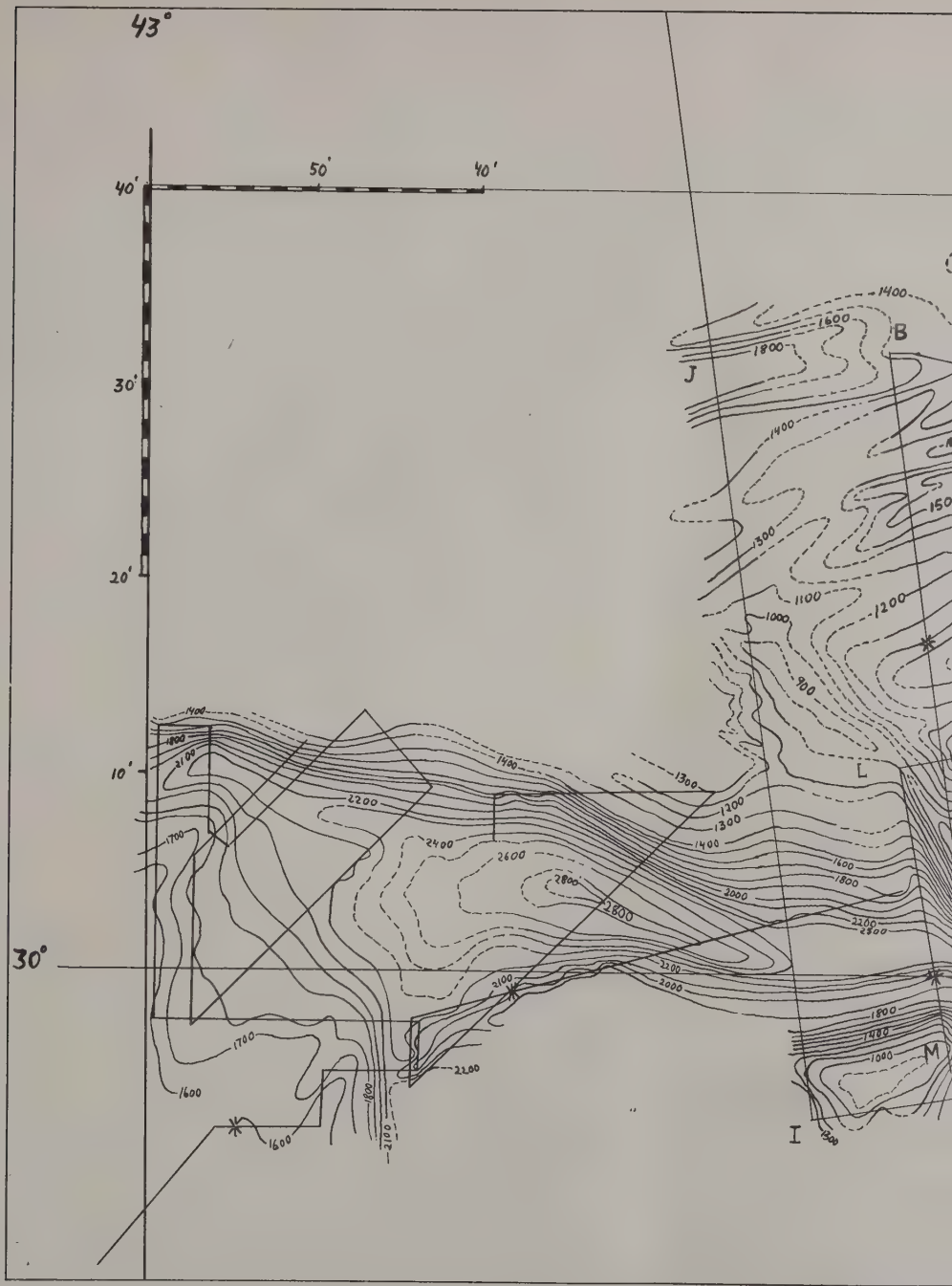
Wiseman, S. D. H., and Seymour Sewell, R. B. (1907) *The floor of the Arabian Sea*, Geol. Mag., vol. 74.

Wust, G. (1939) *Das submarine Relief bei den Azoren*, Abh. Preuss. Akad. Wiss., Phys. Math, Kl., Jahrg. 1939, no. 5, p. 46–58; map 1:3,000,000, Fig. 4, p. 52.

Columbia University, New York, N. Y.

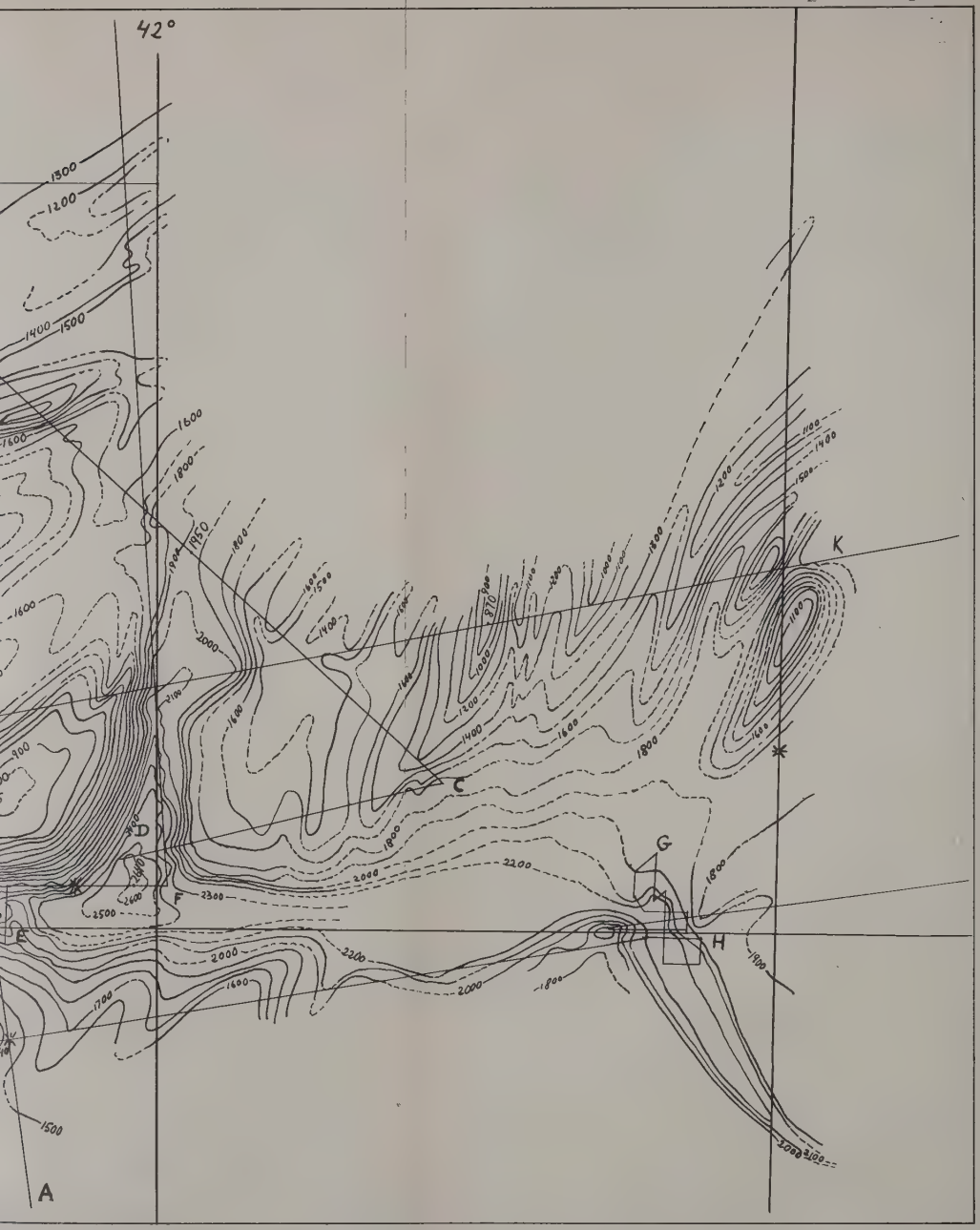
Manuscript Received by the Secretary of the Society, September 7, 1948.

Contribution No. 498, The Woods Hole Oceanographic Institution



SKETCH MAP OF T

Surveyed by the ATLANTIS during the summer of 1947. This trough is
Main Range of the Mid-Atlantic Ridge. From the soundings available, its
respond to those on plates 6 c and d. Contour interval, 100 fathoms Aster



HE EAST-WEST TROUGH

also visible on Plates 2 and 7 from which it may be seen to cut deep into the
estern and eastern extremities seem to slope gently upward. The letters cor-
ks indicate star fixes.

List of Contributions

LIST OF CONTRIBUTIONS

FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

For a list of Contribution Numbers 1 to 200 see previous issues from 1933 to 1942. A separate list of these numbers may be obtained on request.

No. 201. George L. Clarke. The Utilization of Solar Energy by Aquatic Organisms. *Amer. Assoc. Adv. Sci.*, Publ. No. 10, pp. 27–38. 1939.

No. 202. Clinton M. Osborn. The Physiology of Color Change in Flatfishes. *Jour. Exper. Zool.*, Vol. 81, No. 3, pp. 479–515. 1939.

No. 203. Martin D. Burkenroad. Further Observations on Penaeidae of the Northern Gulf of Mexico. *Bull. Bing. Oceanographic Coll.*, Vol. 6, Art. 6, pp. 1–62. 1939.

No. 204. Fred B Phleger, Jr. Foraminifera of Submarine Cores from the Continental Slope. *Bull. Geol. Soc. Amer.*, Vol. 50, pp. 1395–1422. 1939.

No. 205. Talbot H. Waterman, Rudolf F. Nunnemacher, Fenner A. Chace, Jr., and George L. Clarke. Diurnal Vertical Migrations of Deep-water Plankton. *Biol. Bull.*, Vol. 76, No. 2, pp. 256–279. 1939.

No. 206. Sidney C. T. Hsiao. The Reproduction of *Limacina retroversa* (Flem.). *Biol. Bull.* Vol. 76, No. 2, pp. 280–303. 1939.

No. 207. W. H. Johnson and J. E. G. Raymont. The Reactions of the Planktonic Copepod *Centropages typicus*, to Light and Gravity. *Biol. Bull.*, Vol. 77, No. 2, pp. 200–215. 1939.

No. 208. Louis A. Toth. Renal and Vascular Responses to Epinephrine Injections in Glomerular and Aglomerular Fish. *Amer. Jour. Physiol.*, Vol. 126, No. 2, pp. 347–353. 1939.

No. 209. John A. Young, Jr. Minerals from Deep Sea Cores and Surface Deposits of Bermudian Calcareous Sediments. *Amer. Jour. Sci.*, Vol. 237, No. 11, pp. 798–810. 1939.

No. 210. Henry B. Bigelow and William C. Schroeder. Notes on the Fauna above Mud Bottoms in Deep Water in the Gulf of Maine. *Biol. Bull.*, Vol. 76, No. 3, pp. 305–324. 1939.

No. 211. Talbot Howe Waterman. Studies of Deep-sea Angler-fishes (Ceratioidea). I. An historical survey of our present state of knowledge. II. Three new species. *Bull. Mus. Comp. Zool.*, Vol. 85, No. 3, pp. 65–94. 1939.

No. 212. George L. Clarke. The Relation between Diatoms and Copepods as a Factor in the Productivity of the Sea. *Quart. Rev. Biol.*, Vol. 14, No. 1, pp. 60–64. 1939.

No. 213. A. A. Abramowitz. The Pituitary Control of Chromatophores in the Dogfish. *Amer. Nat.*, Vol. 73, pp. 208–218. 1939.

No. 214. George L. Clarke and David D. Bonnet. The Influence of Temperature on the Survival, Growth and Respiration of *Calanus finmarchicus*. *Biol. Bull.*, Vol. 76, No. 3, pp. 371–383. 1939.

No. 215. Floyd M. Soule. Oceanography. Excerpt from International Ice Observation and Ice Patrol Service in the North Atlantic Ocean, Season of 1938. *U. S. Coast Guard Bull.*, No. 28, pp. 113–173. 1940.

No. 216. Bostwick H. Ketchum. The Absorption of Phosphate and Nitrate by Illuminated Cultures of *Nitzschia closterium*. *Amer. Jour. Bot.*, Vol. 26, No. 6, pp. 399–407. 1939.

No. 217. H. R. Seiwell. Some Applications of Statistical Methods to Problems in Modern Physical Oceanography. *Proc. Industrial Statistics Conference*, held at Mass. Inst. Tech. Sept. 8 and 9, 1938. Pitman Publishing Corporation, pp. 156–173. 1939.

No. 218. Pedro J. Bermúdez. Resultados de la Primera Expedicion en las Antillas del Ketch *Atlantis* bajo los Auspicios de las Universidades de Harvard y Habana. Nuevo Género y Especies Nuevas de Foraminiferos. *Mem. Soc. Cub. Hist. Nat.*, Vol. 13, No. 1, pp. 9–12. 1939.

No. 219. Bostwick H. Ketchum. The Development and Restoration of Deficiencies in the Phosphorus and Nitrogen Composition of Unicellular Plants. *Jour. Cell. and Comp. Physiol.*, Vol. 13, No. 3, pp. 373–381. 1939.

No. 220. C. O'D. Iselin. The Influence of Vertical and Lateral Turbulence on the Characteristics of the Waters at Mid-depths. *Trans. Amer. Geophys. Union*, Twentieth Annual Meeting, pp. 414–417. 1939.

No. 221. C. O'D. Iselin. Some Physical Factors which may Influence the Productivity of New England's Coastal Waters. *Sears Found., Jour. Mar. Res.*, Vol. 2, No. 1, pp. 74–85. 1939.

No. 222. Theodor von Brand, Norris W. Rakestraw and Charles E. Renn. Further Experiments on the Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. *Biol. Bull.*, Vol. 77, No. 2, pp. 285–296. 1939.

No. 223. H. R. Seiwell. *Atlantis* Cruise to the Tropical North Atlantic, January to March, 1939. *Trans. Amer. Geophys. Union*, Twentieth Annual Meeting, pp. 418–422. 1939.

No. 224. W. J. Clench and C. G. Aguayo. Notes and Descriptions of New Deep-water Mollusca obtained by the Harvard-Havana Expedition off the Coast of Cuba. II. *Mem. Soc. Cub. Hist. Nat.*, Vol. 13, No. 3, pp. 189–197. 1939.

No. 225. Pedro J. Bermúdez. Resultados de la Primera Expedicion en las Antillas del Ketch *Atlantis* bajo los Auspicios de las Universidades de Harvard y Habana. Foraminiferos del Género Recurvoides, descripción de una Especie Nueva. *Mem. Soc. Cub. Hist. Nat.*, Vol. 13, No. 2, pp. 57–61. 1939.

No. 226. H. R. Seiwell. The Effect of short period Variations of Temperature and Salinity on Calculations in Dynamic Oceanography. *Papers in Physical Oceanography and Meteorology*, Vol. 7, No. 3, pp. 1–32. 1939.

No. 227. H. R. Seiwell. Daily Temperature Variations in the Western North Atlantic. *Jour. du Conseil*, Vol. 14, No. 3, pp. 357–369. 1939.

No. 228. Norris W. Rakestraw, Clifford E. Herrick, Jr., and Wm. D. Urry. The Helium-Neon Content of Sea Water and its Relation to the Oxygen Content. *Jour. Amer. Chem. Soc.*, Vol. 61, pp. 2806–2807. 1939.

No. 229. Edward M. Brooks. Transport and Convergence of the North Atlantic Drift Current Computed from the Average January Pressure Distribution. *Sears Found., Jour. Mar. Res.*, Vol. 2, No. 2, pp. 163–167. 1939.

No. 230. Floyd M. Soule. Consideration of the Depth of the Motionless Surface near the Grand Banks of Newfoundland. *Sears Found., Jour. Mar. Res.*, Vol. 2, No. 3, pp. 169–180. 1939.

No. 231. Charles W. Hock. Decomposition of Chitin by Marine Bacteria. *Biol. Bull.*, Vol. 79, No. 1, pp. 199–206. 1940.

No. 232. Gordon A. Riley. Plankton Studies. II. The Western North Atlantic, May-June, 1939. *Sears Found., Jour. Mar. Res.*, Vol. 2, No. 2, pp. 145–162. 1939.

No. 233. J. T. Nichols. Young Caranx in the Western North Atlantic. *Bull. Bingham Oceanographic Coll.*, Vol. 7, Art. 2, pp. 1–9. 1939.

No. 234. Albert Eide Parr. Quantitative Observations on the Pelagic Sargassum Vegetation of the Western North Atlantic. *Bull. Bingham Oceanographic Coll.*, Vol. 6, Art. 7, pp. 1–94. 1939.

No. 235. R. B. Montgomery. Observations of Vertical Humidity Distribution above the Ocean Surface and their Relation to Evaporation. *Papers in Physical Oceanography and Meteorology*, Vol. 7, No. 4, pp. 1–30. 1940.

No. 236. George L. Clarke. Variation in the Transparency of Three Areas of the Atlantic throughout the Year. *Ecology*, Vol. 20, No. 4, pp. 529–543. 1939.

No. 237. H. R. Seiwell. Anchoring Ships on the High Seas. *U. S. Naval Inst. Proc.*, Vol. 66, No. 12, Whole No. 454, pp. 1733–1740. 1940.

No. 238. D. Q. Anderson. Distribution of Organic Matter in Marine Sediments and its Availability to further Decomposition. *Sears Found., Jour. Mar. Res.*, Vol. 2, No. 3, pp. 225–235. 1939.

No. 239. Henry B. Bigelow. Medusae of the Templeton Crocker and Eastern Pacific *Zaca* Expeditions 1936–1938. *Zoologica*, Vol. 25 (Part 3), pp. 281–321. 1940.

No. 240. Not issued.

No. 241. George L. Clarke. Comparative Richness of Zooplankton in Coastal and Offshore Areas of the Atlantic. *Biol. Bull.*, Vol. 78, No. 2, pp. 226–255. 1940.

No. 242. C. P. Winsor and G. L. Clarke. A Statistical Study of Variation in the Catch of Plankton Nets. *Sears Found., Jour. Mar. Res.*, Vol. 3, No. 1, pp. 1–34. 1940.

No. 243. Pedro J. Bermúdez. Resultados de la Primera Expedicion en las Antillas del Ketch *Atlantis* bajo los Auspicios de las Universidades de Harvard y Habana. Nueva Género y Especies Nuevas de Foraminiferos. *Mem. Soc. Cub. Hist. Nat.*, Vol. 13, No. 4, pp. 247–251. 1939.

No. 244. H. C. Stetson. Oceanography. Chapter in Geology, 1888–1938, Fiftieth Anniversary Volume. *Geol. Soc. Amer.*, pp. 43–69. 1941.

No. 245. R. B. Montgomery. The Present Evidence on the Importance of Lateral Mixing Processes in the Ocean. *Bull. Amer. Meteorol. Soc.*, Vol. 21, No. 3, pp. 87–94. 1940.

No. 246. A. A. Abramowitz, F. L. Hisaw, E. Boettiger and D. A. Papandrea. The Origin of the Diabetogenic Hormone in the Dogfish. *Biol. Bull.*, Vol. 78, No. 2, pp. 189–201. 1940.

No. 247. Clinton M. Osborn. The Experimental Production of Melanin Pigment on the Lower Surface of Summer Flounders *Paralichthys dentatus*. *Proc. Nat. Acad. Sci.*, Vol. 26, No. 3, pp. 155–161. 1940.

No. 248. Elisabeth Deichmann. Report on the Holothurians collected by the Harvard-Havana Expeditions 1938 and 1939, with a revision of the Molpadonia of the Atlantic Ocean. *Mem. Soc. Cub. Hist. Nat.*, Vol. 14, No. 3, pp. 183–240. 1940.

No. 249. Mary Sears and George L. Clarke. Annual Fluctuations in the Abundance of Marine Zooplankton. *Biol. Bull.*, Vol. 79, No. 2, pp. 321–328. 1940.

No. 250. W. J. Clench and C. G. Aguayo. Notes and Descriptions of New Deep-Water Mollusca obtained by the Harvard-Havana Expedition off the Coast of Cuba. III. *Mem. Soc. Cub. Hist. Nat.*, Vol. 14, No. 1, pp. 77–94. 1940.

No. 251. Athelstan F. Spilhaus. A Detailed Study of the Surface Layers of the Ocean in the neighborhood of the Gulf Stream with the aid of Rapid Measuring Hydrographic Instruments. *Sears Found., Jour. Mar. Res.*, Vol. 3, No. 1, pp. 51–75. 1940.

No. 252. R. B. Montgomery. Generalization for Cylinders of Pradtl's Linear Assumption for Mixing Length. *Annals N. Y. Acad. Sci.*, Vol. 44, Art 1, pp. 89–103. 1943.

No. 253. Sidney C. T. Hsiao. Melanosis in the Common Cod, *Gadus callarias L.*, Associated with Trematode Infection. *Biol. Bull.*, Vol. 80, No. 1, pp. 37–44. 1941.

No. 254. Sidney C. T. Hsiao. A New Record of Two Flounders, *Etropus crossotus* Goode & Bean and *Ancylopsetta dilecta* (Goode & Bean) with notes on Post Larval Characters. *Copeia*, No. 3, pp. 195–198. 1940.

No. 255. Austin H. Clark. The Family Antedonidae in the West Tropical Atlantic. *Mem. Soc. Cub. Hist. Nat.*, Vol. 14, No. 2, pp 139–160. 1940.

No. 256. Floyd M. Soule. Oceanographic Conditions in the Grand Banks Region and the Labrador Sea in 1939. Excerpt from International Ice Observation and Ice Patrol Service in the North Atlantic Ocean. Season of 1939. *U. S. Coast Guard Bull.* No. 29, pp. 79–133. 1940.

No. 257. Charles E. Renn. Effects of Marine Muds upon the Aerobic Decomposition of Plankton Materials. *Biol. Bull.*, Vol. 78, No. 3, pp. 454–462. 1940.

No. 258. C. O'D. Iselin. The Necessity of a New Approach to the Study of the Circulation on the Continental Shelf. *Trans. Amer. Geophys. Union*, Twenty-first Annual Meeting, pp. 347–348. 1940.

No. 259. Henry B. Bigelow, Lois Lillick and Mary Sears. Phytoplankton and Planktonic Protozoa of the Offshore Waters of the Gulf of Maine. Part I. Numerical Distribution. *Trans. Amer. Philos. Soc.* Vol. 31, Part 3, pp. 149–191. 1940.

No. 260. Alfred H. Woodcock. Convection and Soaring over the open Sea. *Sears Found., Jour. Mar. Res.*, Vol. 3, No. 3, pp. 248–253. 1940.

No. 261. C. O'D. Iselin. Preliminary Report on Long-Period Variations in the Transport of the Gulf Stream System. *Papers in Physical Oceanography and Meteorology*, Vol. 8, No. 1, pp. 1–40. 1940.

No. 262. Lois C. Lillick. Phytoplankton and Planktonic Protozoa of the Offshore Waters of the Gulf of Maine. Part II. Qualitative Composition of the Planktonic Flora. *Trans. Amer. Philos. Soc.*, Vol. 31, Part 3, pp. 193–237. 1940.

No. 263. H. R. Seiwell. Preliminary Results of Measurements of Temperature and Salinity Variations in the Gulf Stream. *Trans. Amer. Geophys. Union*, Twenty-first Annual Meeting, pp. 349–352. 1940.

No. 264. H. R. Seiwell. Investigation of Internal Waves in the North Atlantic Ocean. Year Book, 1940, *Amer. Philos. Soc.*, pp. 243–246. 1941.

No. 265. William J. Clench. A New Bathyaurinia from off Northern Florida. *Mem. Soc. Cub. Hist. Nat.*, Vol. 14, No. 3, pp. 241–242. 1940.

No. 266. George L. Clarke and Dean F. Bumpus. The Plankton Sampler—an Instrument for Quantitative Plankton Investigations. *Limnolog. Soc. of Amer.*, Spec. Pub. No. 5, pp. 1–8. 1940.

No. 267. Not issued.

No. 268. Theodor von Brand and Norris W. Rakestraw. Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. III. Influence of Temperature and Source and Condition of Water. *Biol. Bull.*, Vol. 79, No. 2, pp. 231–236. 1940.

No. 269. Fenner A. Chace, Jr. Reports on the Scientific Results of the *Atlantis* Expeditions to the West Indies under the joint auspices of the University of Havana and Harvard University. The Brachyuran Crabs. *Torreia*, No. 4, pp. 2–67. 1940.

No. 270. Theodor von Brand and Norris W. Rakestraw. The Determination of Dissolved Organic Nitrogen in Sea Water. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 1, pp. 76–80. 1941.

No. 271. Not issued.

No. 272. Not issued.

No. 273. Charles W. Hock. Marine Chitin-Decomposing Bacteria. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 2, pp. 99–106. 1941.

No. 274. Fenner A. Chace, Jr. The *Atlantis* Expeditions to the West Indies in 1938 and 1939, under the joint auspices of the University of Havana and Harvard University. List of Stations. *Woods Hole Oceanographic Inst.* 1940.

No. 275. R. B. Montgomery and R. B. Sykes, Jr. Table for Density of Sea Water at 0°C and Atmospheric Pressure for Values of Chlorinity between 18.00 and 20.99 according to Knudsen's Formula. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 1, pp. 28–31. 1941.

No. 276. H. R. Seiwell. Summary of Some Results of Internal-Wave Investigations in the North Atlantic. *Trans. Amer. Geophys. Union*, Twenty-second Annual Meeting, pp. 494–498. 1941.

No. 277. R. B. Montgomery. Sea Level Difference Between Key West and Miami, Florida. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 1, pp. 32–37. 1941.

No. 278. Jose T. Acosta. Algunos Foraminiferos Neuvos de las Costas Cubanas. *Torreia*, No. 5, pp. 3–6. 1940.

No. 279. Alfred C. Redfield and Alice Beale. Factors determining the Distribution of Populations of Chaetognaths in the Gulf of Maine. *Biol. Bull.*, Vol. 79, No. 3, pp. 459–487. 1940.

No. 280. Claude E. Zobell. The Effect of Oxygen Tension on the Rate of Oxidation of Organic Matter in Sea Water by Bacteria. *Sears Found., Jour. Mar. Res.*, Vol. 3, No. 3, pp. 211–223. 1940.

No. 281. Alfred C. Redfield. The Effect of the Circulation of Water on the Distribution of the Calanoid Community in the Gulf of Maine. *Biol. Bull.*, Vol. 80, No. 1, pp. 86–110. 1941.

No 282. C. G. Lalicker and P. J. Bermúdez. Some Foraminifera of the Family Textulariidae Collected by the first *Atlantis* Expedition. *Torreia*, No. 8, pp. 1–20. 1941.

No. 283. William C. Schroeder. Some Deep Sea Fishes from the North Atlantic. *Copeia*, No. 4, pp. 231–238. 1940.

No. 284. George Wald. Vitamins A in Invertebrate Eyes. *Amer. Jour. Physiol.*, Vol. 133, No. 2, pp. 479–480. 1941.

No. 285. Hubert Lyman Clark. Reports on the Scientific Results of the *Atlantis* Expeditions to the West Indies, under the joint auspices of the University of Havana and Harvard University. The Echinoderms (other than Holothurians). *Mem. Soc. Cub. Hist. Nat.*, Vol. 15, No. 1, pp. 1–154. 1941.

No. 286. Floyd M. Soule. Physical Oceanography — The Grand Banks Region and the Labrador Sea in 1940. Excerpt from International Ice Observation and Ice Patrol Service in the North Atlantic Ocean. Season of 1940. *U. S. Coast Guard Bull.*, pp. 36–89. 1942.

No. 287. Gordon A. Riley. Plankton Studies. IV. Georges Bank. *Bull. Bingham Oceanographic Coll.*, Vol. 7, Art. 4, pp. 1–73. 1941.

No. 288. R. B. Montgomery and Athelstan F. Spilhaus. Examples and Outline of Certain Modifications in Upper-Air Analysis. *Jour. Aeronautical Sciences*, Vol. 8, No. 7, pp. 1–19. 1941.

No. 289. W. J. Clench and C. G. Aguayo. Notes and Descriptions of New Deep-Water Mollusca Obtained by the Harvard-Havana Expedition off the Coast of Cuba. IV. *Mem. Soc. Cub. Hist. Nat.*, Vol. 15, No. 2, pp. 177–180. 1941.

No. 290. Athelstan F. Spilhaus. Fine Structure of the Edge of the Gulf Stream. *Trans. Amer. Geophys. Union*, Twenty-second Annual Meeting, Part II, pp. 478–484. 1941.

No. 291. H. R. Seiwell. An Analysis of Vertical Oscillations in the southern North Atlantic. *Proc. Amer. Philos. Soc.*, Vol. 85, No. 2, pp. 136-158. 1942.

No. 292. Theodor von Brand and Norris W. Rakestraw. Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. IV. Interrelationship of Various Stages; Influence of Concentration and Nature of Particulate Matter. *Biol. Bull.* Vol. 81, No. 1, pp. 63–69. 1941.

No. 293. Niels Haugaard and Laurence Irving. The Influence of Temperature upon the Oxygen Consumption of the Cunner (*Tautogolabrus adspersus* Walbaum) in Summer and in Winter. *Jour. Cell. and Comp. Physiol.*, Vol. 21, No. 1, pp. 19–26. 1943.

No. 294. Alfred H. Woodcock. Surface Cooling and Streaming in Shallow Fresh and Salt Waters. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 2, pp. 153–161. 1941.

No. 295. Lester V. Whitney. The Angular Distribution of Characteristic Diffuse Light in Natural Waters. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 2, pp. 122–131. 1941.

No. 296. Clinton M. Osborn. Studies on the Growth of Integumentary Pigment in the Lower Vertebrates. *Biol. Bull.*, Vol. 81, No. 3, pp. 341-351. 1941.

No. 297. Fred B Phleger, Jr. Foraminifera of Submarine Cores from the Continental Slope, Part 2. *Bull. Geol. Soc. Amer.*, Vol. 53, pp. 1073–1098. 1942.

No. 298. P. F. Scholander, Niels Haugaard and Laurence Irving. A Volumetric Respirometer for Aquatic Animals. *Review of Sci. Instruments*, Vol. 14, No. 2, pp. 48–51. 1943.

No. 299. Mary Sears. Notes on the Phytoplankton on Georges Bank in 1940. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 3, pp. 247–257. 1941.

No. 300. Talbot Howe Waterman. A Comparative Study of the Effects of Ions on Whole Nerve and Isolated Single Nerve Fiber Preparations of Crustacean Neuromuscular Systems. *Jour. Cell. and Comp. Physiol.* Vol. 18, No. 1, pp. 109–126. 1941.

No. 301. F. G. Walton Smith. Effect of Water Currents Upon the Attachment Growth of Barnacles. *Biol. Bull.*, Vol. 90, No. 1, pp. 51–70. 1946.

No. 302. G. A. Edwards and Laurence Irving. The Influence of Temperature and Season upon the Oxygen Consumption of the Sand Crab, *Emerita talpoida* Say. *Jour. Cell. and Comp. Physiol.*, Vol. 21, No. 2, pp. 169–182. 1943.

No. 303. R. B. Montgomery. Transport of the Florida Current off Havana. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 3, pp. 198–220. 1941.

No. 304. Richard E. Lee. The Occurrence of Female Swordfish in southern New England Waters, with a Description of their Reproduction Condition. *Copeia*, No. 2, pp. 117–119. 1942.

No. 305. R. B. Montgomery and M. J. Pollak. Sigma-T Surfaces in the Atlantic Ocean. *Sears Found., Jour. Mar. Res.*, Vol. 5, No. 1, pp. 20–27. 1942.

No. 306. George L. Clarke. Observations on Transparency in the southwestern section of the North Atlantic Ocean. *Sears Found., Jour. Mar. Res.*, Vol. 4, No. 3, pp. 221–230. 1941.

No. 307. Robert W. Pennak. Harpacticoid Copepods from some Intertidal Beaches near Woods Hole, Massachusetts. *Trans. Amer. Micro. Soc.*, Vol. 61, No. 3, pp. 274–285. 1942.

No. 308. Alfred C. Redfield. The Processes Determining the Concentration of Oxygen, Phosphate and other Organic Derivatives within the Depths of the Atlantic Ocean. *Papers in Physical Oceanography and Meteorology*, Vol. 9, No. 2, pp. 1–22. 1942.

No. 309. William C. Schroeder. Results of Haddock Tagging in the Gulf of Maine from 1923 to 1932. *Sears Found., Jour. Mar. Res.*, Vol. 5, No. 1, pp. 1–19. 1942.

No. 310. W. H. Johnson. Effect of Light on Copepods as Food for Passamaquoddy Herring. *Jour. Fish. Res. Bd. Canada*, 5(4), pp. 365–376. 1942.

No. 311. Charles E. Renn. Demonstration of Labyrinthula Parasite in Eel-Grass from the Coast of California. *Science*, Vol. 95, No. 2457, pp. 122. 1942.

No. 312. C. O'D. Iselin. Interaction between the Hydrosphere and the Atmosphere. *Trans. N. Y. Acad. Sci.*, Series II. Vol. 4, No. 3, pp. 99-106. 1942.

No. 313. G. A. Edwards and Laurence Irving. The Influence of Season and Temperature upon the Oxygen Consumption of the Beach Flea, *Talorchestia megalopthalma*. *Jour. Cell. and Comp. Physiol.*, Vol. 21, No. 2, pp. 183–189. 1943.

No. 314. Earl H. Myers. Rate at which Foraminifera are Contributed to Marine Sediments. *Jour. Sed. Petrology*, Vol. 12, No. 2, pp. 92–95. 1942.

No. 315. Gordon A. Riley. The Relationship of Vertical Turbulence and Spring Diatom Flowerings. *Sears Found., Jour. Mar. Res.*, Vol. 5, No. 1, pp. 67–87. 1942.

No. 316. Earl H. Myers. Biological Evidence as to the Rate at which Tests of Foraminifera are Contributed to Marine Sediments. *Jour. of Paleontology*, Vol. 16, No. 3, pp. 397–398. 1942.

No. 317. Richard E. Lee. The Hypophysis of the Broad-billed Swordfish, *Xiphias gladius* L. *Biol. Bull.*, Vol. 82, No. 3, pp. 401–412. 1942.

No. 318. Athelstan F. Spilhaus. Maps of the Whole World Ocean. *Geog. Rev.*, Vol. 32, No. 3, pp. 431–435. 1942.

No. 319. Gordon A. Riley. Physiological Aspects of Spring Diatom Flowerings. *Bull. Bingham Oceanographic Coll.*, Vol. 8, Art 4, pp. 1–53. 1943.

No. 320. Olga Hartman. Report on the Scientific Results of the *Atlantis* Expeditions to the West Indies under the joint auspices of the University of Havana and Harvard University. The Polychaetous Annelida. *Mem. Soc. Cub. Hist. Nat.*, Vol. 16, No. 2, pp. 89–104. 1942.

No. 321. Theodor von Brand, Norris W. Rakestraw and J. William Zabor. Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. V. Factors Influencing the Length of the Cycle; Observations upon the Gaseous and Dissolved Organic Nitrogen. *Biol. Bull.*, Vol. 83, No. 2, pp. 273–282. 1942.

No. 322. Fenner A. Chace, Jr. Reports on the Scientific Results of the *Atlantis* Expeditions to the West Indies, under the joint auspices of the University of Havana and Harvard University. The Anomuran Crustacea. I. Galatheida (Families Chirostylidae, Galatheidae and Porcellanidae). *Torreia*, No. 11, pp. 1–106. 1942.

No. 323. William Schallek. The Reaction of Certain Crustacea to Direct and to Diffuse Light. *Biol. Bull.*, Vol. 84, No. 1, pp. 98–105. 1943.

No. 324. Richard E. Lee. Notes on the Color Changes of the Sea Robin (*Prionotus strigatus* Cuvier) with special reference to the Erythrophores. *Jour. Exper. Zool.*, Vol. 91, No. 2, pp. 131–153. 1942.

No. 325. Selman A. Waksman, Donald B. Johnstone and Cornelia L. Carey. The Effect of Copper upon the Development of Bacteria in Sea Water and the Isolation of Specific Bacteria. *Sears Found., Jour. Mar. Res.*, Vol. 5, No. 2, pp. 136–152. 1943.

No. 326. Robert W. Pyle. The Histogenesis and Cyclic Phenomena of the Sinus Gland and X-Organ in Crustacea. *Biol. Bull.*, Vol. 85, No. 2, pp. 87–102. 1943.

No. 327. Earl H. Myers. Life Activities of Foraminifera in Relation to Marine Ecology. *Proc. Amer. Philos. Soc.*, Vol. 86, No. 3, pp. 439–458. 1943.

No. 328. George L. Clarke, E. Lowe Pierce and Dean F. Bumpus. The Distribution and Reproduction of *Sagitta elegans* on Georges Bank in Relation to the Hydrographical Conditions. *Biol. Bull.*, Vol. 85, No. 3, pp. 201–226. 1943.

No. 329. A. A. Abramowitz, F. L. Hisaw and D. N. Papandrea. The Occurrence of a Diabetogenic Factor in the Eyestalks of Crustaceans. *Biol. Bull.*, Vol. 86, No. 1, pp. 1–5, 1944.

No. 330. Richard E. Lee. A Quantitative Survey of the Invertebrate Bottom Fauna in Menemsha Bight. *Biol. Bull.*, Vol. 86, No. 2, pp. 83–97. 1944.

No. 331. Alfred H. Woodcock. A Theory of Surface Water Motion deduced from the Wind-Induced Motion of the Physalia. *Sears Found., Jour. Mar. Res.*, Vol. 5, No. 3, pp. 196–205. 1944.

No. 332. Louis W. Hutchins. An Annotated Check-List of the Salt-Water Bryozoa of Long Island Sound. *Trans. Conn. Acad. Arts Sci.*, Vol. 36, pp. 533–551. 1945.

No. 333. Henry B. Bigelow and William C. Schroeder. New Sharks from the Western North Atlantic. *Proc. New Engl. Zool. Club*, Vol. 23, pp. 21–36. 1944.

No. 334. W. J. Clench and C. G. Aguayo. A New Tropical Buccinum From Cuba. *Rev. Soc. Malacol.*, Vol. 2, No. 2, pp. 67–68. 1944.

No. 335. Bostwick H. Ketchum, John D. Ferry, Alfred C. Redfield and Arthur E. Burns, Jr. Evaluation of Anti-fouling Paints by Leaching Rate Determinations. *Ind. Eng. Chem.*, Vol. 37, pp. 456–460. 1945.

No. 336. George T. Scott. The Influence of H-ion Concentration on the Mineral Composition of *Chlorella pyrenoidosa*. *Jour. Cell. and Comp. Physiol.*, Vol. 25, No. 1, pp. 37–44. 1945.

No. 337. George T. Scott. The Mineral Composition of Phosphate Deficient Cells of *Chlorella pyrenoidosa* during the Restoration of Phosphate. *Jour. Cell. and Comp. Physiol.*, Vol. 26, No. 1, pp. 35–42. 1945.

No. 338. Fred B Phleger, Jr. Vertical Distribution of Pelagic Foraminifera. *Amer. Jour. Sci.*, Vol. 243, pp. 377–383. 1945.

No. 339. Warren H. Yudkin. Occurrence of Thiaminase in Marine Teleosts. *Proc. Soc. Exper. Biol. and Med.*, Vol. 60, pp. 268–269. 1945.

No. 340. Irwin M. Newell. Studies on the Morphology and Systematics of the Family Halarachnidae Oudemans 1906 (Acari, Parasitoidae). *Bull. Bingham Oceanographic Coll.*, Vol. 10, Art. 4, pp. 235–266. 1947.

No. 341. Nelson Marshall. Observations on the Comparative Ecology and Life History of two Sea Robins, *Prionotus carolinus* and *Prionotus evolans strigatus*. *Copeia*, No. 3, pp. 118–144. 1946.

No. 342. John D. Ferry and Dayton E. Carritt. Action of Antifouling Paints. I. Solubility and Rate of Solution of Cuprous Oxide in Sea Water. *Ind. Eng. Chem.*, Vol. 38, pp. 612–617. 1946.

No. 343. M. Juul Hvorslev and Henry C. Stetson. Free-Fall Coring Tube: A New Type of Gravity Bottom Sampler. *Bull. Geol. Soc. Amer.*, Vol. 57, pp. 935–950. 1946.

No. 344. Fred B Phleger, Jr. and Walter A. Hamilton. Foraminifera of two Submarine Cores from the North Atlantic Basin. *Bull. Geol. Soc. Amer.*, Vol. 57, pp. 951–966. 1946.

No. 345. John D. Ferry and Gordon A. Riley. Action of Antifouling Paints. II. Solubilities of Antifouling Toxics in Sea Water. *Ind. Eng. Chem.*, Vol. 38, pp. 699–701. 1946.

No. 346. John D. Ferry and Bostwick H. Ketchum. Action of Antifouling Paints. III. Maintenance of the Leaching Rate of Antifouling Paints Formulated with Insoluble, Impermeable Matrices. *Ind. Eng. Chem.*, Vol. 38, pp. 806–810. 1946.

No. 347. Bostwick H. Ketchum, John D. Ferry and Arthur E. Burns, Jr. Action of Antifouling Paints. IV. Maintenance of Leaching Rate of Antifouling Paints Formulated with Soluble Matrices. *Ind. Eng. Chem.*, Vol. 38, pp. 931–936. 1946.

No. 348. Maurice Ewing, Allyn Vine, and J. L. Worzel. Photography of the Ocean Bottom. *Jour. Optical Soc. Amer.*, Vol. 36, No. 6, pp. 307–321. 1946.

No. 349. C. M. Pomerat and C. M. Weiss. The Influence of Texture and Composition of Surface on the Attachment of Sedentary Marine Organisms. *Biol. Bull.*, Vol. 91, No. 1, pp. 57–65. 1946.

No. 350. Marshall Schalk. A Study of Textural Changes in a Beach by repeated Samplings. *Jour. Sed. Petrology*, Vol. 16, No. 2, pp. 43–51. 1946.

No. 351. Maurice Ewing, G. P. Woollard, A. C. Vine, and J. L. Worzel. Recent Results in Submarine Geophysics. *Bull. Geol. Soc. Amer.*, Vol. 57, pp. 909–934. 1946.

No. 352. Gordon A. Riley and Dean F. Bumpus. Phytoplankton-Zooplankton Relationships on Georges Bank. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 1, pp. 33–47. 1946.

No. 353. Gordon A. Riley. Factors Controlling Phytoplankton Populations on Georges Bank. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 1, pp. 54–73. 1946.

No. 354. H. R. Seiwell. Military Oceanography in Tactical Operations of World War II. *Trans. Amer. Geophys. Union*, Vol. 27, No. 5, pp. 677–681. 1946.

No. 355. Henry Stommel. A Summary of the Theory of Convection Cells. *Annals N. Y. Acad. Sci.*, Vol. 48, Art. 8, pp. 715–726. 1947.

No. 356. A. H. Woodcock and Jeffries Wyman. Convective Motion in Air over the Sea. *Annals N. Y. Acad. Sci.*, Vol. 48, Art. 8, pp. 749–776. 1947.

No. 357. R. B. Montgomery. Introduction: Problems Concerning Convective Layers. *Annals N. Y. Acad. Sci.*, Vol. 48, Art. 8, pp. 707–714. 1947.

No. 358. Richard A. Craig. Observations of Vertical Temperature and Humidity Distributions in the Convective Layers above the Sea Surface. *Annals N. Y. Acad. Sci.*, Vol. 48, Art. 8, pp. 783–788. 1947.

No. 359. H. A. Panofsky. Radiative Cooling in the Lowest Layers of an Atmosphere Warmer than the Ground. *Jour. Meteorology*, Vol. 4, No. 1, pp. 35–37. 1947.

No. 360. George L. Clarke. Poisoning and Recovery in Barnacles and Mussels. *Biol. Bull.*, Vol. 92, No. 1, pp. 31–72. 1947.

No. 361. R. B. Montgomery. Over-water Refraction of 10-cm. Electromagnetic Radiation. *Bull. Amer. Meteorol. Soc.*, Vol. 28, No. 1, pp. 1–8. 1947.

No. 362. Richard A. Craig. Measurements of Temperature and Humidity in the lowest 1000 feet of the Atmosphere over Massachusetts Bay. *Papers in Physical Oceanography and Meteorology*, Vol. 10, No. 1, pp. 1–47. 1946.

No. 363. George L. Clarke. Dynamics of Production in a Marine Area. *Ecological Monographs*, Vol. 16, No. 4, pp. 322–335. 1946.

No. 364. Fred B. Phleger, Jr. Foraminifera of three Submarine Cores from the Tyrrhenian Sea. *Kungl. Vet.-o. Vitterh. Samh. Handl.*, F. 6, Ser. B, Bd 5, No. 5, pp. 1–19. 1947.

No. 365. Henry Stommel. Entrainment of Air into a Cumulus Cloud. *Jour. Meteorology*, Vol. 4, No. 3, pp. 91–94. 1947.

No. 367. Henry Stommel. Note on the Use of the T-S Correlation for Dynamic Height Anomaly Computations. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 2, pp. 85–92. 1947.

No. 368. Gordon A. Riley. A Theoretical Analysis of the Zooplankton Population of Georges Bank. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 2, pp. 104–113. 1947.

No. 369. Gordon A. Riley. Seasonal Fluctuations of the Phytoplankton Population in New England Coastal Waters. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 2, pp. 114–125. 1947.

No. 370. William S. von Arx. A Salinometer for use in Brackish Water. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 2, pp. 139–145. 1947.

No. 371. Norris W. Rakestraw and Theodor von Brand. Decomposition and Regeneration of Nitrogenous Organic Matter in Sea Water. VI. The Effect of Enzyme Poisons. *Biol. Bull.*, Vol. 92, No. 2, pp. 110–114. 1947.

No. 372. Alfred H. Woodcock and Gordon A. Riley. Patterns in Pond Ice. *Jour. Meteorology*, Vol. 4, No. 3, pp. 100–101. 1947.

No. 373. Alfred H. Woodcock and Henry Stommel. Temperatures Observed near the Surface of a Fresh-Water Pond at Night. *Jour. Meteorology*, Vol. 4, No. 3, pp. 102–103. 1947.

No. 374. Louis W. Hutchins. The Bases for Temperature Zonation in Geographical Distribution. *Ecological Monographs*, Vol. 17, No. 3, pp. 325–335. 1947.

No. 375. Norris W. Rakestraw. Oxygen Consumption in Sea Water over long Periods. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 3, pp. 259–263. 1947.

No. 376. Frances L. Parker. Foraminifera of the Continental Shelf from the Gulf of Maine to Maryland. *Bull. Mus. Comp. Zool.*, Vol. 100, No. 2, pp. 213–241. 1948.

No. 377. Bostwick H. Ketchum. The Biochemical Relations between Marine Organisms and their Environment. *Ecological Monographs*, Vol. 17, No. 3, pp. 309–315. 1947.

No. 378. F. G. Walton Smith. Mechanical Control of Ship-Bottom Fouling by means of Air Bubbles. *Jour. Fla. Acad. Sci.*, Vol. 9, Nos. 3–4, pp. 153-161. 1947.

No. 379. H. R. Seiwell. Oceangraphic Factors in Underwater Depth Determination by Aerial Photography. *Photogrammetric Eng.*, Vol. 15, No. 1, pp. 171–176. 1949.

No. 380. H. J. Turner, Jr., D. M. Reynolds and A. C. Redfield. Chlorine and Sodium Pentachlorophenate as Fouling Preventives in Sea Water Conduits. *Ind. Eng. Chem.*, Vol. 40, pp. 450–453. 1948.

No. 381. H. R. Seiwell. Resume of Military Oceanography in World War II. *The Military Engineer*, Vol. 39, No. 259, pp. 202–210. 1947 (not included in *Collected Reprints*).

No. 382. H. R. Seiwell. Tidal Illumination Diagrams. *Science*, Vol. 106, No. 2743, pp. 76–77. 1947.

No. 383. R. B. Montgomery and P. A. Sheppard. Comments on P. A. Sheppard's Direct Measurement of Ground Stress. *Quart. Jour. Roy. Meteor. Soc.*, Vol. 73, Nos. 317–318, pp. 459–463. 1947.

No. 384. Edward S. Deevey, Jr. Life Tables for Natural Populations of Animals. *Quart. Rev. Biol.*, Vol. 22, No. 4, pp. 283–314. 1947.

No. 385. Charles M. Weiss. The Comparative Tolerances of some Fouling Organisms to Copper and Mercury. *Biol. Bull.*, Vol. 93, No. 1, pp. 56–63. 1947.

No. 386. H. R. Seiwell. Investigation of Underwater Pressure Records and Simultaneous Sea Surface Patterns. *Trans. Amer. Geophys. Union*, Vol. 28, No. 5, pp. 722–724. 1947.

No. 387. Frederick C. Fuglister. Average Monthly Sea Surface Temperatures of the Western North Atlantic Ocean. *Papers in Physical Oceanography and Meteorology*, Vol. 10, No. 2, pp. 1–25. 1947.

No. 388. R. B. Montgomery. Viscosity and Thermal Conductivity of Air and Diffusivity of Water Vapor in Air. *Jour. Meteorology*, Vol. 4, No. 6, pp. 193–196. 1947.

No. 389. Alfred H. Woodcock. Note Concerning Human Respiratory Irritation Associated with High Concentrations of Plankton and Mass Mortality of Marine Organisms. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 1, pp. 56–62. 1948.

No. 390. Charles M. Weiss. An Observation on the Inhibition of Marine Wood Destroyers by Heavy Fouling Accumulation. *Ecology*, Vol. 29, No. 1, p. 120. 1948.

No. 391. Georgiana B. Deevey. The Zooplankton of Tisbury Great Pond. *Bull. Bingham Oceanographic Coll.*, Vol. 12, Art. 1, pp. 1–44. 1948.

No. 392. Charles M. Weiss. Observations on the Abnormal Development and Growth of Barnacles as Related to Surface Toxicity. *Ecology*, Vol. 29, No. 1, pp. 116–119. 1948.

No. 393. J. C. Decius. Dimensional Analysis: An Approach from Transformation Theory and a Criterion for Scaling Model Experiments. *Jour. Franklin Inst.*, Vol. 245, No. 5, pp. 379–387. 1948.

No. 394. Alfred C. Redfield. Characteristics of Sea Water. In *The Corrosion Handbook*, pp. 1111–1122. H. H. Uhlig, Editor. Published by John Wiley & Sons, New York. 1948.

No. 395. George C. Whiteley, Jr. The Distribution of Larger Plankton Crustacea on Georges Bank. *Ecological Monographs*, Vol. 18, No. 2, pp. 233–264. 1948.

No. 396. William C. Schroeder. Notes on the Diet of the Goosefish, *Lophius americanus*. *Copeia*, No. 3, p. 396. 1947.

No. 397. Louis W. Hutchins and Margaret Scharff. Maximum and Minimum Monthly Mean Sea Surface Temperatures chartered from the "World Atlas of Sea Surface Temperatures". *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 3, pp. 264–268. 1947.

No. 398. Bostwick H. Ketchum. Action of Antifouling Paints. V. Use of Glycine Solutions as Accelerated Test of Availability of Toxic. *Ind. Eng. Chem.*, Vol. 40, pp. 249–253. 1948.

No. 399. Bostwick H. Ketchum and John C. Ayers. Action of Antifouling Paints. VI. Effect of Nontoxic Pigments on the Performance of Antifouling Paints. *Ind. Eng. Chem.*, Vol. 40, p. 2124–2127. 1948.

No. 400. Charles M. Weiss. The Effect of Illumination and Stage of Tide on the Attachment of Barnacle Cyprids. *Biol. Bull.*, Vol. 93, No. 3, pp. 240–249. 1947.

No. 401. W. S. Butcher. A New Species of *Nonion* (Foraminifera) from the Woods Hole Region. *Contr. Cushman Lab. Foram. Res.*, Vol. 24, (1), No. 308, pp. 21–23. 1948.

No. 402. Edward S. Deevey, Jr. On the Date of the Last Rise of Sea Level in Southern New England, with Remarks on the Grassy Island Site. *Amer. Jour. Sci.*, Vol. 246, pp. 329–352. 1948.

No. 403. Charles M. Weiss. The Abnormal Development of Tunicates Attached to Glass Surfaces Adjacent to Antifouling Paints. *Ecology*, Vol. 29, No. 2, pp. 215–218. 1948.

No. 404. Charles M. Weiss. The Seasonal Occurrence of Sedentary Marine Organisms in Biscayne Bay, Florida. *Ecology*, Vol. 29, No. 2, pp. 153–172. 1948.

No. 405. R. B. Montgomery. Vertical Eddy Flux of Heat in the Atmosphere. *Jour. Meteorology*, Vol. 5, No. 6, pp. 265–274. 1948.

No. 406. Hilary B. Moore. The Zooplankton of the Upper Waters of the Bermuda Area of the North Atlantic. *Sears Found., Jour. Mar. Res.*, Vol. 12, Art. 2, pp. 1–97. 1949. (Not included in *Collected Reprints*.)

No. 407. H. R. Seiwell. Evaluation of Sea-Surface Roughness from Underwater-Pressure Recordings. *Trans. Amer. Geophys. Union*, Vol. 29, No. 2, pp. 197–201. 1948.

No. 408. Henry Stommel. The Westward Intensification of Wind-Driven Ocean Currents. *Trans. Amer. Geophys. Union*, Vol. 29, No. 2, pp. 202–206. 1948.

No. 409. Sidney C. Hsiao. The Simple Micromethod for Rapid Extraction of Lipids. *Science*, Vol. 107, No. 2766, pp. 24–25. 1948.

No. 410. Austin H. Clark. Some Interesting Starfishes and Brittle-Stars Dredged by the *Atlantis* in the Mid-Atlantic. *Jour. Wash. Acad. Sci.*, Vol. 38, No. 2, pp. 75–78. 1948.

No. 411. Alfred C. Redfield and Charles M. Weiss. The Resistance of Metallic Silver to Marine Fouling. *Biol. Bull.*, Vol. 94, No. 1, pp. 25–28. 1948.

No. 412. J. B. Hersey and H. B. Moore. Progress Report on Scattering Layer Observations in the Atlantic Ocean. *Trans. Amer. Geophys. Union*, Vol. 29, No. 3, pp. 341–354. 1948.

No. 413. Gardner Emmons. Vertical Distributions of Temperature and Humidity over the Ocean between Nantucket and New Jersey. *Papers in Physical Oceanography and Meteorology*, Vol. 10, No. 3, pp. 1–89. 1947.

No. 414. W. T. Edmondson and Yvette H. Edmondson. Measurements of Production in Fertilized Salt-Water. *Sears Found., Jour. Mar. Res.*, Vol. 6, No. 3, pp. 228–245. 1947.

No. 415. J. Lamar Worzel and Maurice Ewing. Propagation of Sound in the Ocean: Explosion Sounds in Shallow Water. *Geol. Soc. Amer.* Mem. 27, pp. i–vi, 1–53. 1948.

C. L. Pekeris. Propagation of Sound in the Ocean: Theory of Propagation of Explosive Sound in Shallow Water. *Geol. Soc. Amer.* Mem. 27, pp. i–viii, 1–117. 1948.

Maurice Ewing and J. Lamar Worzel. Propagation of Sound in the Ocean: Long-Range Sound Transmission. *Geol. Soc. Amer.* Mem. 27, pp. i–v, 1–35. 1948. (not included in *Collected Reprints*)

No. 416. Sidney Cornell. The Collapse of Long Cylindrical Shells under External Pressure. *Soc. Exper. Stress Analysis*, Vol. 6, No. 1, pp. 111–114. 1948.

No. 417. Alfred H. Woodcock. The Swimming of Dolphins. *Nature*, Vol. 161, p. 602. 1948.

No. 418. J. M. Richardson, A. B. Arons and R. R. Halverson. Hydrodynamic Properties of Sea Water at the Front of a Shock Wave. *Jour. Chem. Physics*, Vol. 15, No. 11, pp. 785–794. 1947.

No. 419. Bostwick H. Ketchum and Jean Keen. Unusual Phosphorus Concentrations in the Florida "Red Tide" Sea Water. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 1, pp. 17–21. 1948.

No. 420. C. A. Barnes, D. F. Bumpus and John Lyman. Ocean Circulation in Marshall Islands Area. *Trans. Amer. Geophys. Union*, Vol. 29, No. 6, pp. 871–876. 1948.

No. 421. William S. von Arx. The Circulation Systems of Bikini and Rongelap Lagoons. *Trans. Amer. Geophys. Union*, Vol. 29, No. 6, pp. 861–870. 1948.

No. 422. William L. Ford. Radiological and Salinity Relationships in the Water at Bikini Atoll. *Trans. Amer. Geophys. Union*, Vol. 30, No. 1, pp. 46–54. 1949.

No. 423. R. B. Montgomery. Ivory's Psychrometric Formula and the Concepts of Equivalent Temperature and Wet-Bulb Temperature. *Jour. Meteorology*, Vol. 5, No. 3, pp. 113–115. 1948.

No. 424. Parker D. Trask, Fred B Phleger, Jr., and Henry C. Stetson. Recent Changes in Sedimentation in the Gulf of Mexico. *Science*, Vol. 106, No. 2759, pp. 460–461. 1947.

No. 425. George L. Clarke and David W. Bishop. The Nutritional Value of Marine Zooplankton with a Consideration of its Use as an Emergency Food. *Ecology*, Vol. 29, No. 1, pp. 54–71. 1948.

No. 426. J. Lamar Worzel. Ocean Bottom Sampler for Ships Under Way. *Geophysics*, Vol. 13, No. 3, pp. 452–456. 1948.

No. 427. Clinton M. Osborn. Factors Influencing the Growth of Integumentary Pigment in Fishes. I. The Role of Light. *Proc. Soc. Exper. Biol. and Med.*, Vol. 67, pp. 440–445. 1948.

No. 428. A. W. Jacobson. An Instrument for Recording Continuously the Salinity, Temperature, and Depth of Sea Water. *Trans. Amer. Inst. Elec. Eng.*, Vol. 67, pp. 1–9. 1948.

No. 429. Fred B Phleger, Jr. Foraminifera of a Submarine Core from the Caribbean Sea. *Kungl. Vet.-o. Vitterh. Samh. Handl.*, F. 6, Ser. B, Bd. 5, No. 14, pp. 1–9. 1948.

No. 430. A. B. Arons, J. P. Slifko and A. Carter. Secondary Pressure Pulses due to gas Globe Oscillation in Underwater Explosions. I. Experimental Data. *Jour. Acoust. Soc. Amer.*, Vol. 20, No. 3, pp. 271–276. 1948.

No. 431. A. B. Arons. Secondary Pressure Pulses due to Gas Globe Oscillation in Underwater Explosions. II. Selection of Adiabatic Parameters in the Theory of Oscillation. *Jour. Acoust. Soc. Amer.*, Vol. 20, No. 3, pp. 277–282. 1948.

No. 432. Talbot H. Waterman. Studies on Deep-Sea Angler-Fishes (Ceratioidea). *Jour. Morphology*, Vol. 82, No. 2, pp. 81–149. 1948.

No. 433. L. N. Liebermann. Reflection of Sound from Coastal Sea Bottoms. *Jour. Acoust. Soc. Amer.*, Vol. 20, No. 3, pp. 305–309. 1948.

No. 434. Charles M. Weiss. Seasonal and Annual Variations in the Attachment and Survival of Barnacle Cyprids. *Biol. Bull.*, Vol. 94, No. 3, pp. 236–243. 1948.

No. 435. H. R. Seiwell. Sea Surface Roughness Measurements in Theory and Practice. *Annals N. Y. Acad. Sci.*, Vol. 51, Art. 3, pp. 483–501. 1949.

No. 436. H. R. Seiwell. Results of Research on Surface Waves of the Western North Atlantic. I. Investigation of Bottom Pressure Fluctuations and Surface Waves. II. Results of Sea Roughness Determinations in the Vicinity of Woods Hole, Massachusetts and Bermuda. *Papers in Physical Oceanography and Meteorology*, Vol. 10, No. 4, pp. 1–56. 1948.

No. 438. Arthur A. Klebba. Details of Shore-Based Wave Recorder and Ocean Wave Analyzer. *Annals N. Y. Acad. Sci.*, Vol. 51, Art. 3, pp. 533–544. 1949.

No. 439. Athelstan F. Spilhaus. Drop Size, Intensity and Radar Echo of Rain. *Jour. Meteorology*, Vol. 5, No. 4, pp. 161–164. 1948.

No. 440. Athelstan F. Spilhaus and Arthur R. Miller. The Sea Sampler. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 370–385. 1948.

No. 441. Gordon A. Riley and Samy Gorgy. Quantitative Studies of Summer Plankton Populations of the Western North Atlantic. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 2, pp. 100–121. 1948.

No. 442. Alfred C. Redfield. The Exchange of Oxygen across the Sea Surface. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 347–361. 1948.

No. 443. Patricia A. Langwell. Inhomogeneities of Turbulence, Temperature, and Moisture in the West Indies Trade-wind Region. *Jour. Meteorology*, Vol. 5, No. 5, pp. 243–246. 1948.

No. 444. Fred B. Phleger, Jr. Origin and Deposition of Deep Sea Sediments. *Trans. Amer. Geophys. Union*, Vol. 30, No. 2, pp. 180–182. 1949.

No. 445. B. Haurwitz. The Effect of Ocean Currents on Internal Waves. *Sears Found., Jour. Mar. Res.* Vol. 7, No. 3, pp. 217–228. 1948.

No. 446. Bostwick H. Ketchum, Cornelia L. Carey and Margaret Briggs. Preliminary Studies on the Viability and Dispersal of Coliform Bacteria in the Sea. *In* Limnological Aspects of Water Supply and Waste Disposal. Ed. F. R. Moulton and and Florence Hitzel. *Publ. Amer. Assoc. Adv. Sci.*, pp. 64–73. 1949.

No. 447. Henry B. Bigelow and William C. Schroeder. New Genera and Species of Batoid Fishes. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 543–566. 1948.

No. 448. Hilary B. Moore. A Camera for Producing One-Dimensional Reduction in Narrow Records. *Sears Found., Jour. Mar. Res.*, Vol. 8, No. 1, pp. 21–23. 1949.

No. 449. A. B. Arons and D. R. Yennie. Energy Partition in Underwater Explosion Phenomena. *Rev. Modern Physics*, Vol. 20, No. 3, pp. 519–536. 1948 (Not included in *Collected Reprints*).

No. 450. J. B. Hersey and Maurice Ewing. Seismic Reflections from beneath the Ocean Floor. *Trans. Amer. Geophys. Union*, Vol. 30, No. 1, pp. 5–14. 1949.

No. 451. C. O'D. Iselin and Frederick C. Fuglister. Some Recent Developments in the Study of the Gulf Stream. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 317–329. 1948.

No. 452. Norris W. Rakestraw and Dayton E. Carritt. Some Seasonal Chemical Changes in the Open Ocean. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 362–369. 1948.

No. 453. Henry Stommel. The Theory of the Electric Field Induced in Deep Ocean Currents. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 386–392. 1948.

No. 454. Parker D. Trask. Oceanography and Geosynclines. *Sears Found., Jour. Mar. Res.*, Vol. 7, No. 3, pp. 679–685. 1948.

No. 455. L. N. Liebermann. Reflection of Underwater Sound from the Sea Surface. *Jour. Acoust. Soc. Amer.*, Vol. 20, No. 4, pp. 498–503. 1948.

No. 456. Lewis F. Richardson and Henry Stommel. Note on Eddy Diffusion in the Sea. *Jour. Meteorology*, Vol. 5, No. 5, pp. 238–240. 1948.

No. 457. Joanne Starr Malkus. Effects of Wind Shear on Some Aspects of Convection. *Trans. Amer. Geophys. Union*, Vol. 30, No. 1, pp. 19–25. 1949.

No. 458. Alfred H. Woodcock and Mary M. Gifford. Sampling Atmospheric Sea-Salt Nuclei over the Ocean. *Sears Found., Jour. Mar. Res.*, Vol. 8, No. 2, pp. 177–197. 1949.

No. 459. William L. Ford. The Field Use of a Salinity-Temperature-Depth Recorder. *Sears Found., Jour. Mar. Res.*, Vol. 8, No. 1, pp. 84–96. 1949.

No. 460. William E. Schevill and Barbara Lawrence. Underwater Listening to the White Porpoise (*Delphinapterus Leucas*). *Science*, Vol. 109, No. 2824, pp. 143–144. 1949.

No. 461. H. R. Seiwell and George P. Wadsworth. A New Development in Ocean Wave Research. *Science*, Vol. 109, No. 2829, pp. 271–274. 1949.

No. 462. Harry J. Turner, Jr., John C. Ayers and Charles L. Wheeler. Report on Investigations of the Propagation of the Soft-Shell Clam, *Mya arenaria*. *Div. Mar. Fish., Dept. Cons., Com. Mass.*, pp. 1–61. 1948.

No. 463. Floyd M. Soule and E. R. Challender. Discussion of some of the Effects of Winds on Ice Distribution in the Vicinity of the Grand Banks and the Labrador Shelf. *U. S. Coast Guard Bull., No.* 33, pp. 59–61. 1949.

No. 464. Gordon A. Riley, Henry Stommel and D. F. Bumpus. Quantitative Ecology of the Plankton of the Western North Atlantic. *Bull. Bingham Oceanographic Coll.*, Vol. 12, Art. 3, pp. 1–169. 1949. (Not included in *Collected Reprints.*)

No. 466. David M. Pratt. Experiments in the Fertilization of a Salt Water Pond. *Sears Found., Jour. Mar. Res.*, Vol. 8, No. 1, pp. 36–59. 1949.

No. 468. Richard A. Craig. Vertical Eddy Transfer of Heat and Water Vapor in Stable Air. *Jour. Meteorology*, Vol. 6, No. 2, pp. 123–133. 1949.

No. 469. Henry Stommel. Trajectories of Small Bodies Sinking Slowly through Convection Cells. *Sears Found., Jour. Mar. Res.*, Vol. 8, No. 1, pp. 24–29. 1949.

No. 470. Henry W. Menard, Jr. Synthesis of Sand Mixtures. *Jour. Sed. Petrology*, Vol. 19, No. 2, pp. 71–77. 1949.

No. 471. Austin H. Clark. Echinoderms from the Mid-Atlantic Dredged by the *Atlantis* in the Summer of 1948. *Jour. Wash. Acad. Sci.* Vol. 39, No. 11, pp. 371–377. 1949.

No. 472. Gordon A. Riley and Ruth Von Arx. Theoretical Analysis of Seasonal Changes in the Phytoplankton of Husan Harbor, Korea *Sears. Found., Jour. Mar. Res.*, Vol. 8, No. 1, pp. 60–72. 1949.

No. 473. Bostwick H. Ketchum, Lois Lillick and Alfred C. Redfield. The Growth and Optimum Yields of Unicellular Algae in Mass. Culture. *Jour. Cell. and Comp. Physiol.*, Vol. 33, No. 3, pp. 267–279. 1949.

No. 474. Bostwick H. Ketchum and Alfred C. Redfield. Some Physical and Chemical Characteristics of Algae Grown in Mass. Culture. *Jour. Cell. and Comp. Physiol.*, Vol. 33, No. 3, pp. 281–299. 1949.

No. 478. Richard A. Craig and R. B. Montgomery. Evaporation (Measured) from Ocean into Hydrostatically Stable Air. *Jour. Meteorology*, Vol. 6, No. 6, pp. 426-427. 1949.

No. 484. Fred B. Phleger. The Foraminifera. *In* The Boylston Street Fishweir II. *Papers Robert S. Peabody Found. Archaeol.*, Vol. 4, No. 1, pp. 99–108. 1949.

No. 485. Fred B. Phleger, Jr. Submarine Geology and Pleistocene Research. *Bull. Geol. Soc. Amer.*, Vol. 60, pp. 1457–1462. 1949.

No. 486. H. R. Seiwell. The Principles of Time Series Analyses Applied to Ocean Wave Data. *Proc. Nat. Acad. Sci.*, Vol. 35, No. 9, pp. 518–528. 1949.

No. 496. Henry Stommel. Horizontal Diffusion Due to Oceanic Turbulence. *Sears Found., Jour. Mar. Res.*, Vol. 8, No. 3, pp. 199–225. 1949.

No. 498. Ivan Tolstoy and Maurice Ewing. North Atlantic Hydrography and the Mid-Atlantic Ridge. *Bull. Geol. Soc. Amer.*, Vol. 60, pp. 1527–1540. 1949.